AN ASSESSMENT OF SUSPENDED SEDIMENT TRANSPORT IN ARCTIC ALASKAN RIVERS

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AN ASSESSMENT OF SUSPENDED SEDIMENT TRANSPORT IN ARCTIC ALASKAN RIVERS

A

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By

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Abstract

Provided here is an initial assessment of suspended sediment transport in several rivers on the North Slope of Alaska. This study was divided into two parts: the Umiat project, which involved the Chandler, Anaktuvuk and Itkillik Rivers, and the NPR-A study, which considered Prince, Seabee and Fish Creeks, as well as a brief look at the Ikpikpuk River, Otuk Creek, Judy Creek and the Ublutuoch River. Methods used included depth-integrated suspended sediment samples, grab samples, automatic pump-style samplers, discharge measurements, bed sediment grain size analysis and the inclusion of a variety of meteorological measurements from other projects. With slightly less than two years of data collection from May 2011 to September 2012, an initial analysis was completed. Suspended sediment rating curves developed for the Anaktuvuk and Chandler Rivers over the two-year study period revealed a strong correlation between suspended sediment concentration (SSC) and discharge. The most data was collected for the Anaktuvuk and Chandler Rivers; on these rivers, suspended sediment discharge was also analyzed, showing that over 90% of suspended sediment transport occurred during the spring melt period in 2011. Spring melt was not measured in 2012, so analysis was only completed for 2011.

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Abbreviations

AKDOT & PF= Alaska Department of Transportation and Public Facilities

BLM = Bureau of Land Management

NPR-A = National Petroleum Reserve – Alaska

Q = water discharge

q_s = suspended sediment discharge

SSC = suspended sediment concentration

SWE = snow water equivalent

UAF = University of Alaska Fairbanks

WERC = Water and Environmental Research Center

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1 Introduction

The hydrologic and sedimentologic regime of arctic rivers is quite different from their temperate brethren. Long, severe winters and the presence of permafrost create conditions of little to no baseflow throughout the winter, while rapid runoff is typical of spring breakup. Permafrost is defined as ground that remains frozen for two years or longer (Williams and Smith 1989). This undoubtedly generates sediment transport regimes that differ dramatically from the well-studied transport regime of temperate rivers; however, sediment transport in the arctic has not been studied in the same depth as in temperate rivers. There are many reasons for this lack of comprehensive studies, including the remote location of many arctic rivers, harsh weather and the difficult logistics of working in the arctic.

Arctic rivers such as those on the North Slope of Alaska are greatly influenced by the climate in which they develop. Snow can be present for eight months of the year and the entire region is underlain by continuous permafrost (Osterkamp and Payne 1981), clearly differentiating arctic rivers from more temperate rivers. It is well known that permafrost has a strong influence on the hydrology of a region (Dingman and Koutz 1974; Woo 1986; McNamara et al. 1998); however the effect on sediment transport is less well understood. Sediment supply and transport is influenced by a variety of factors that are common to both arctic and temperate rivers, including basin size, climate, precipitation intensity and duration, runoff volume, underlying geology, vegetation, ice cover and the large scale relief within the watershed (Gordeev 2006). With this many factors to consider it is understandable why so few in depth studies have been completed in the arctic. However, even among studies that have looked at sediment transport in arctic and ice-affected rivers, many do not consider rivers that freeze to the bed over the winter. Methods for estimating the sediment transport that occurs under ice have been offered (Ettema et al. 2000; Ettema and Daly 2004), though they are most concerned with the effects downstream of flow-regulating dams and reservoirs. A comprehensive review of sediment transport in ice-affected rivers by Turcotte et al. (2011) considers the increase in sediment transport that can occur because of ice rafting, freeze-thaw cycles, and ice jams, but does not specifically review rivers that are located in regions underlain by continuous permafrost.

The principal objective of this study was to complete an initial analysis of suspended sediment transport in arctic Alaska. This thesis presents work done on suspended sediments from May of 2011 to September of 2012. There are two projects discussed; first is the Umiat Corridor Hydrology Project, which considered the Anaktuvuk, Chandler and Itkillik Rivers. Second is the National Petroleum Reserve – Alaska Hydrology Study, the main rivers of which were Prince, Seabee and Fish Creeks. Suspended sediment concentrations and discharge are discussed for each river, as well as bed sediment grain size distributions, suspended sediment rating curves and suspended sediment discharges for selected rivers. It was hypothesized that suspended sediment transport regimes would be closely related to discharge on each river, and that the majority of suspended sediment transport would occur during spring breakup. In addition, due to the large differences in basin areas, it was expected that each river would have a unique sediment transport regime.

2 Background

2.1 Suspended Sediment Concentration in Arctic Rivers

Suspended sediment concentration (SSC) is a measure of the dry weight of inorganic sediments in relation to the mass of water in a particular sample; in this work the units for SSC are always milligrams of sediment per liter of water. One of the first studies to look at suspended sediment transport in arctic Alaska was done on the Colville River in 1962 (Arnborg et al. 1967). The total suspended load, as well as dissolved organic material, was measured; 75% of the transport occurred during breakup, a transport regime confirmed by numerous other studies on arctic rivers (Clark et al. 1988; Braun et al. 2000; Forbes and Lamoureux 2005). As well as having a runoff hydrograph dominated by snowmelt, the highest SSC values are also typically measured during spring melt (Lewkowicz and Wolfe 1994; Forbes and Lamoureux 2005). While arctic rivers are typically considered to have a hydrograph that is snowmelt driven, summer storms can, however, transport enormous volumes of suspended sediments if conditions are right. This is discussed further in this work.

2.2 Meteorological Influences on Suspended Sediment Concentration

Many factors influence the SSC of a river: hydrologic, meteorological and geologic conditions can greatly increase or decrease the load of a specific river or river reach. Snow, rain and underlying geology are prime examples of factors that can influence the SSC of a river both at a specific point in time and throughout the flow season, particularly through the hydrologic runoff response of the watershed to rain and snow.

2.2.1 Snow

Arctic rivers typically exhibit a snowmelt dominated hydrograph (Braun et al. 2000; Forbes and Lamoureux 2005; Cockburn and Lamoureux 2008), making snow an extremely important variable to consider as an input to the river system. The snow water equivalent (SWE) is a common measure of the water contained in a snowpack, and is frequently measured at the end of spring when the snowpack is at its greatest. Numerous studies of arctic nival streams have confirmed that a relationship between SWE and suspended sediment concentrations exists, and that SWE is in fact more important an influence than melt energy available (Braun et al. 2000; Forbes and Lamoureux 2005; Cockburn and Lamoureux 2008; McDonald and Lamoreux 2009). When the snowpack is in the initial melt period there is typically a significant linear correlation between temperature and discharge, as well as temperature and SSC, but the strength of these relationships decreases as the snowpack is depleted (Forbes and Lamoureux 2005). It is important to note, however, that the presence of ice and snow in the channel during the initial flow period can substantially reduce bed scour and sediment transport loads (Forbes 1975; Oatley 2002; McNamara et al. 2008). This indicates that when considering the total sediment yield of a watershed throughout a season, the SWE is more important than spring melt conditions. Also important to consider is the size of the watershed; “larger watersheds require greater hydrologic inertia to produce substantial discharge” (Forbes and Lamoureux 2005). Snowmelt is such an important time period for sediment transport in arctic rivers that it dwarfs suspended sediment transport which occurs throughout the rest of the flow season. While no study appears to have been completed that compares SSC in arctic rivers before and after ice is in the channel during spring melt, the studies that have been finished do confirm that the snowmelt period typically moves the majority of suspended sediments in a flow season. Braun et al. (2000) found that 88% of the annual sediment load into Lake Sophia in Nunavut, Canada occurred during snowmelt. Forbes and Lamoureux (2005) saw similar results on the Lord Lindsay River, Nunavut, Canada where 93% of total suspended sediment transport occurred during snowmelt annually. Also important to consider is the percentage of total seasonal runoff that occurs during snowmelt, to confirm that the large percentages of the annual suspended sediment load measured during snowmelt is not simply related to the quantity of discharge. On the Lord Lindsay River 80% of the total annual runoff occurred during snowmelt (Forbes and Lamoureux 2005). Interestingly, 80% of the annual runoff into Lake Sophia from the Sophia River also occurred during snowmelt (Braun et al. 2000).

2.2.2 Rain

The effect of summer storms on SSC varies widely between previous studies of arctic catchments. Simply considering changes in discharge is also likely to provide clues about a specific watershed's response to a summer storm. Larger watersheds will typically respond slower and less dramatically to a rain event than a similarly located but smaller watershed (Forbes and Lamoureux 2005). While snowmelt dominates the hydrograph of most arctic streams, and is a visually awe-inspiring event, summer rains are rarely so intense or affect such a large percentage of the watershed. These storms may, however, have a large impact on the suspended sediment discharge of a catchment as they occur when sediment sources are exposed and available for erosion (Cogley and McCann 1976). Under the right conditions a summer storm can transport the majority of the suspended sediment in a flow season, with the flow season considered the period between spring breakup and the beginning of freeze-up (typically mid-May to mid-September in arctic Alaska) (Kane et al. 2003; Lewis et al. 2005).

These extreme events are difficult to capture and require a high number of samples in a short period of time. However in the Canadian arctic, a large event was captured in 1998 (Lewis et al. 2005). During this event, SSC rose to 83,760 mg/L; in addition 39% of the annual sediment yield for the flow season occurred during this single large rain event, while 45% of the sediment yield occurred during spring melt. While runoff from a recent rain event did contribute to this mid-summer peak in SSC, it was enhanced by warm air temperatures and increased pore water content, as well as increased thickness of the active layer that contributed to rapid mass wasting (Lewis et al. 2005). An extreme rainfall event was also recorded in the Alaskan arctic in 1999 on the Kuparuk River by Kane et al. (2003). The hydrograph peak recorded during this rain event was 3 times greater than any previously measured peak, including those caused by the annual spring melt.

2.2.3 Geology

Sediment supply in a given watershed is primarily dependent on two factors: the geology and the topography of the watershed. Studies of arctic catchments have found large inter-annual variability in sediment supply within the same catchment (Church and Ryder 1972; Lewkowicz and Wolfe 1994), indicating that the availability of sediment supplies is unpredictable in arctic catchments. It is important to note that many of the studies of sediment supply in arctic climates have been done on glacial rivers. However, among periglacial rivers, sediment supplies to rivers are frequently river terraces and moraines near the channel, as well as nearby slopes (Woo and McCann 1994). In addition to these sources, during warm periods of time, such as the summer, many of these features experience subsidence and slumping (i.e. thermokarsting), further increasing sediment supply and possibly sediment delivery directly to the river channel (Lewkowicz and Young 1990).

2.3 Methods

Most studies of SSC include the collection of water samples for later analysis in a lab. There are many methods for accomplishing this, and for the purpose of this discussion they will be broken into two groups: depth-integrated samples and point samples. Depth-integrated samples are designed to continuously accumulate a sample from the river by being lowered and raised at a constant rate through the entire water column (Edwards and Glysson 1988; Diplas et al. 2008). Taking a single, vertically-integrated sample is a common technique for obtaining the mean SSC throughout the water column (Diplas et al. 2008). Point samples are taken from a specific location in the water column, typically either via a grab sample from the bank or a boat, or by automatic pump style devices. Automatic pump style devices, such as the Teledyne Isco 3700 Autosampler, are popular in studies of remote streams (Wren et al. 2000; Bogen and Bonses 2003; Richards and Moore 2003). These devices do not require personnel to be present, and can typically take 24 or 36 samples before needing to be emptied and reset. Programming can change the frequency of sampling, and allow for greater temporal resolution during important periods of flow season. The drawback of these devices, however, is that they essentially act as point samples and only provide a measurement at one specific water depth. In addition to only providing a water sample from one specific depth, the intake for pump style devices is generally close to the banks and therefore may not always be in the main channel current. As water depths change, the location of the pump intake as a percentage of depth will change, affecting the percentage of suspended sediments that are being captured. The maximum concentration of suspended sediments is carried at 60% of water depth (Garcia 2008), and the location of the pump intake as a percentage of water depth is not fixed. As a result it is very important to correlate the samples taken by a pump style device to those taken by a depth-integrating sampler along the main river channel. Previous studies have compared point samples taken by an automatic pump-device (i.e. Isco) to those taken by a depth-integrated sample. Gurnell et al. (1992) showed a linear relationship between samples taken by the Isco and the depth-integrated sampler, although the Isco shows a higher variability in SSC concentrations. Other studies have also supported the accuracy of samples taken by Isco-type devices (Wren et al. 2000; Richards and Moore 2003).

Turbidity is a measure of the haziness of a solution caused by suspended solids, which may or may not be visible to the naked eye. Turbidity meters measure turbidity by detecting light scattering and attenuation in the water column, and is measured in relative units that have no physical significance (Campbell Scientific 2008). Turbidity meters are a less common method for monitoring SSC than automatic pump-style devices, but they have been used with some success. In arctic rivers where personnel are frequently not present and data is typically sparse, turbidity meters can provide a detailed view of SSC fluctuations. While SSC can be correlated to flow and estimated from discharge values, turbidity is typically a better proxy for SSC if the turbidimeter can be kept free of fouling and debris (Lewis 2003). Turbidity is influenced by sediment size, and therefore the same SSC could have multiple turbidities associated with it as sediment sizes vary (Foster et al. 1992). However, unless sediment sources are rapidly changing, turbidity can be related to SSC; this relationship is usually linear (Lewis 1996; Lewis 2003; Lewis et al. 2005). In addition, samples taken by pump-style devices and depth-integrating samplers do not usually have great temporal resolution on very short time scales, but the turbidimeter will pick up these short-term fluctuations (Cockburn and Lamoureux 2008).

3 Umiat Corridor Hydrology Project

3.1 Study Sites

The three rivers considered in this study are the Anaktuvuk, Chandler and Itkillik Rivers (Table 3.1). These three rivers are part of the Umiat Corridor Hydrology Project (Figure 3.1), a study funded by the Alaska Department of Transportation and Public Facilities (AKDOT&PF). These rivers are located on the North Slope of Alaska; the Anaktuvuk, Chandler and Itkillik Rivers all flow north from the foothills of the Brooks Range into the Colville River, which empties into the Arctic Ocean. All are underlain by continuous permafrost that ranges from 250 to 600 m thick (Osterkamp and Payne 1981), with permafrost thickening as one heads north. In this region, the active layer is usually 50 cm, but may vary between 25 and 100 cm. Depth of the active layer is contingent on several factors, including slope, aspect, soil type, vegetation type and soil moisture (Hinzman et al. 1991; Hinzman et al. 1998). With snow on the ground for seven to nine months of the year, breakup does not generally begin until mid-May in the basin headwaters in the mountains (Kane et al. 2012). As one heads north, breakup occurs later in the spring; near the coast it may be late May or early June. During the two years of meteorological monitoring of this study, the coldest month was usually December or January, with the average monthly temperature between -29.3°C and -10.8°C. July was the warmest month with temperatures between 7.5°C and 12.6°C. A low of -49.8°C was recorded at the Anaktuvuk River meteorological station in January of 2010, and a high of 30.9°C at the Chandler River in June of 2011 (Kane et al. 2012).

Vegetation in this region is characterized by low shrubs and tussocked tundra. Typical vegetation in the foothills includes sedges (*Eriophorum veginatum, Carex bigelowi*), dwarf shrubs (*Ledum palustre, Betula nana, Vaccinium vitis-idaea*), as well as willow (*Salix pulchra*) and some alders (*Alnus* ssp.) along the river valleys (Jones et al. 2009). In the mountains there is no vascular vegetation at elevations over 900 m, and at these elevations the vegetation mat is mainly lichens and sedges and the plant cover is open (Slack et al. 1979).

Table 3.1 Coordinates of gauge sites for the Chandler, Anaktuvuk and Itkillik Rivers.

	Latitude	**Longitude**
Chandler River	69° 17’ 0.30” N	151° 24’ 16.14” W
Anaktuvuk River	69° 27’ 51.00” N	151° 10’ 07.00” W
Itkillik River	68° 51’ 59.46” N	150°2’ 24.00” W

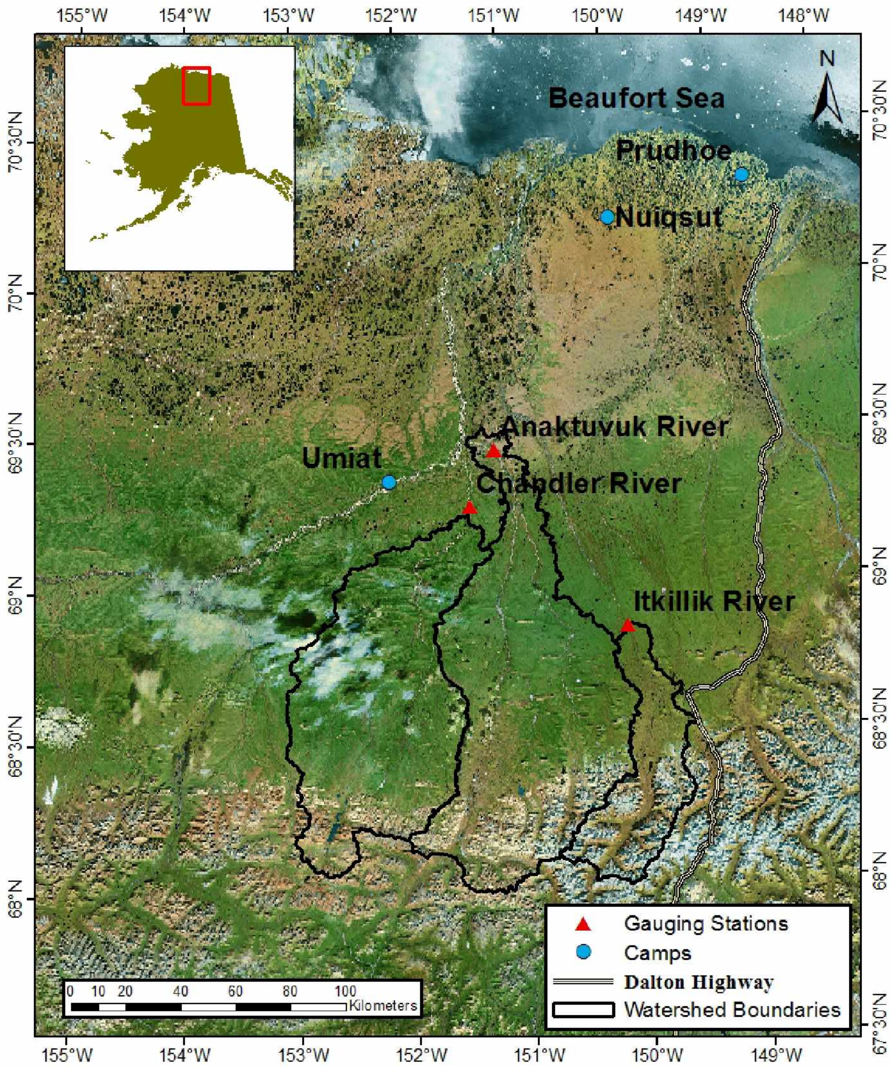

Figure 3.1 Study sites on the North Slope of Alaska: the Anaktuvuk, Chandler and Itkillik Rivers.

3.1.1 Chandler River

Westernmost of the rivers considered as part of the Umiat project was the Chandler River (Figure 3.2), which joins the Colville River near the Umiat camp. Originating at Chandler Lake, the river flows for approximately 225 kilometers to the study site, and has a basin area of 5800 km^2 upstream of the study site. The study site was located at an elevation of 86 meters above sea level, and in 2011 the initiation of flow occurred on 5/22/2011 at 10:30 AM. The Chandler River has numerous side channels that experience flow at high water levels, with the majority of flow occurring in a single main channel. Gauging was done at a location where no side channels are typically active. At this location the channel width ranges between 40 and 210 meters, with a width of 210 meters measured on 5/26/2011. For comparison the width was 42 meters on 7/9/2011. Spring melt was not measured in 2012, and so no dates or widths are offered for comparison.

Figure 3.2 The Chandler River on 5/27/2011 (top) and 8/22/2012 (bottom). The top photo was taken after snowmelt, the bottom photo was at the end of summer during a typical lower flow period. Flow direction is indicated by the arrow.

3.1.2 Anaktuvuk River

The Anaktuvuk River (Figure 3.3) originates at a glacier in the Endicott Mountains, centrally located within the Brooks Range. The gauge site is located east of the Chandler River gauge site, as well as further north. From this origin to the study site is a distance of 215 kilometers, and a basin area of 7000 km^2. Downstream of the study site the Anaktuvuk River empties into the Colville River, just north of the Colville River's confluence with the Chandler River. Located at an elevation of 31 meters above sea level, the Anaktuvuk River gauge site was both the farthest north study site and at the lowest elevation. In 2011 flow was initially observed on 5/22/2011, with the flow front occurring over the ice. The Anaktuvuk River at the gauge site is quite braided, although the flow is in a single channel at most discharges. The width of the channel ranged between approximately 100 and 330 meters, with a maximum measured width of 321 meters on 5/29/2011; on 7/7/2011 the width was 95 meters.

Figure 3.3 The Anaktuvuk River on 5/24/2011 (top) and 8/20/2012 (bottom). At the time of the top photo water levels were beginning to fall after the peak from spring melt; the bottom photo was taken during a period of lower flow. Flow direction is indicated by the arrow.

3.1.3 Itkillik River

The Itkillik River (Figure 3.4) was the easternmost river considered as part of this study. The study site was located at an elevation of 429.2 meters above sea level, in the foothills of the Brooks Range. Upstream of the study site the Itkillik watershed is approximately 1900 km^2, and the river runs for 153 kilometers from headwaters in the Brooks Range to the study site. As seen in Figure 3.1, the Itkillik watershed is a long, narrow basin which originates in the Endicott Mountains. Breakup typically occurs in mid-May at the study site, with flow beginning in 2011 on 5/19/2011. At the location of the gauge site on the Itkillik River the flow is in a single channel, with a width that ranged between approximately 30 and 80 meters.

Figure 3.4 The Itkillik River on 6/2/2011 (top) and 8/23/2012 (bottom). The top photo was taken as water levels were falling after the spring melt, the bottom photo was from a lower flow period. Flow direction is indicated by the arrow.

3.2 Methods

Methods for obtaining sediment transport data are numerous, but have to be carefully chosen for use on the North Slope of Alaska. The accuracy of these methods is a function of the data collected in the field. Sampling options are restricted by the remote nature of the field sites which allows for access only via helicopter during many portions of the year, limiting the time that researchers can spend at each site. Methods include characterizing the bed sediment distribution, depth integrated suspended sediment sampling, automated sampling for suspended sediments, turbidity and discharge measurements, as well as climate data collection. The goal of this combination of methods was to achieve a fairly continuous monitoring record of suspended sediment data in each river without researchers having to be in the field at all times. The overall research goal was to collect a cohesive data set on suspended sediments on the North Slope of Alaska, in order to allow for an initial analysis of this suspended sediment transport over the warm season.

3.2.1 Bed Sediment Distribution

To determine the bed sediment distribution at each river a photographic sampling method (Church et al. 1987) was used. The bed sediment distribution was calculated for each river using a taped grid of 0.9-m by 0.9-m (Figure 3.5) on exposed gravel bars near the end of the spring field-work. Within this 0.9-m square grid, nine sections were demarcated. One rock in each section was numbered and brought back to the lab in order to be precisely weighed and measured. Photographs of each grid were taken, with the sediments measured and separated into size intervals at later dates. In the photographs only those sediments large enough to be seen without magnification and un-obscured by other sediments were measured. This method of photo-sampling analyzed only sediments that were in the topmost layer of bed sediments.

This approach was useful for the remote field work as it required minimal time and effort while in the field, however it did have limitations. Studies have found that there can be a negative-bias in sizing due to some sediments being partially hidden, as well as due to the downward tilt many streambed sediments exhibit (Church et al. 1987). This downward tilt is typified by sediments that are turned downward at an angle and partially covered by other bed sediments.

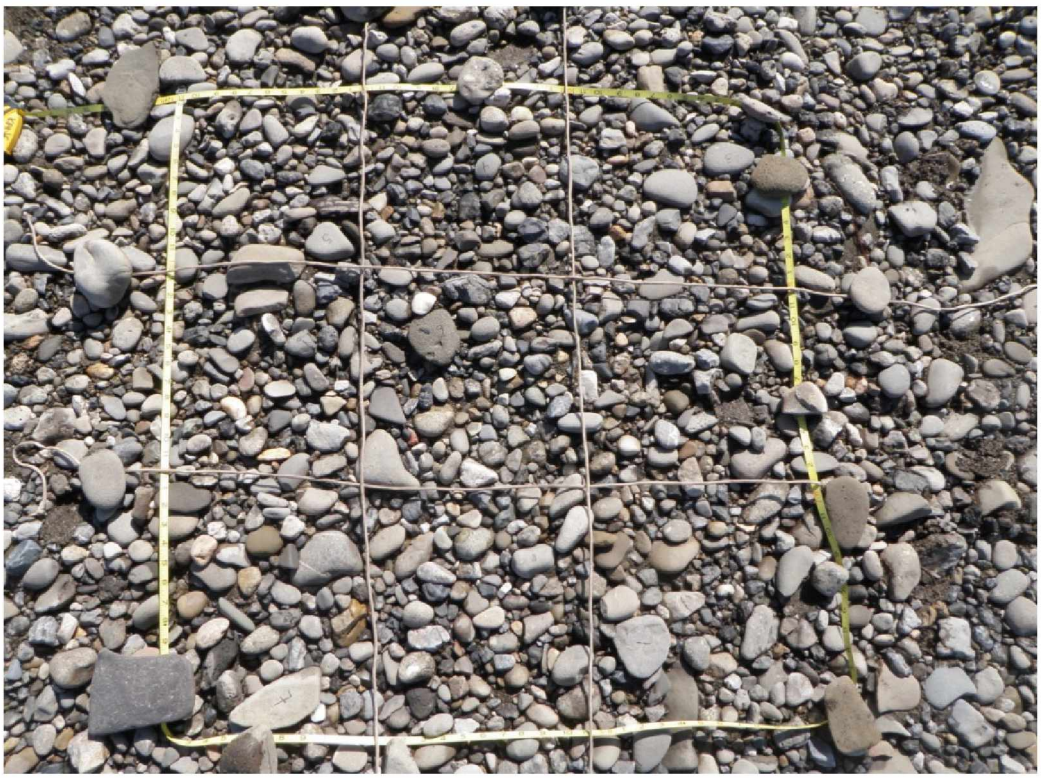

Figure 3.5 Example of 0.9-meters by 0.9-meters grid on an exposed gravel bar for photo-sampling analysis of bed sediment distribution.

3.2.2 Suspended Sediment Concentration

Stream water samples were taken with Isco 3700 Portable Autosamplers, in order to determine the SSC. In the spring of 2011 samples were taken four times daily on the Anaktuvuk, Chandler and Itkillik Rivers, and once daily at all other times throughout the summer. In 2012 fieldwork activities only involved the summer months, thus breakup was missed. During this period Iscos collected a sample once daily on all three rivers. Deployment of the intake hose varied by season; during spring breakup it was unfeasible to elevate the hose above the river bed due to dangerous working conditions in the river channels. For most other periods the hose was elevated roughly 15 cm off the river bed to prevent the collection of sediments that were not in suspension.

Integrated suspended sediment samples were also taken on each river using a Rickly Hydrological depth-integrating sampler (Model DH76), with a one-quarter inch nozzle. In the spring of 2011 integrated samples were taken daily on the Anaktuvuk and Chandler Rivers, and roughly once per month on all rivers throughout the summers of 2011 and 2012. Two to three integrated samples were taken at each time; each sample was not taken in the exact same location, but all were collected in the main thalweg of the channel. In general, the distribution of suspended sediments was assumed to be approximately constant across the main channel (Wren et al. 2000). Therefore if the SSC value from the Isco was correlated to the SSC value of the depth-integrated sample, a picture of SSC throughout the entire cross-section was achieved. The calculated SSC of the two to three concurrent depth-integrated samples were later averaged.

Samples taken by the Iscos and the depth-integrated sampler were analyzed in the lab to determine SSC. Following ASTM Standard 3977-97, the samples were vacuum filtered through Whatman GF/C glass microfiber filters with particle retention of 1.2 μm. In this method the filters were prewashed and dried at 105°C for 1 hour, weighed, and then filtered and dried at

105°C for four hours. The percentage of organic matter in each sample was then determined using ASTM Standard 2974 (Test Method C), in which samples are placed in a muffle furnace at 440°C for twelve hours. For this study only the inorganic solids, referred to as SSC, were considered.

Samples taken by the Iscos were considered to be point samples, and were not necessarily demonstrative of suspended sediment conditions throughout the entire river. As a result the SSC values from the Iscos must be compared to those taken by the depth-integrated sampler, and a relationship was developed between the two sample types. This allowed for a correction of the Isco SSC values that is more representative of the entire river cross-section.

3.2.3 Suspended Sediment Concentration Rating Curves

Suspended sediment rating curves were developed for the Anaktuvuk and Chandler Rivers using SSC values from the depth-integrated samplers. These samples were plotted against measured discharge values (methods for measuring water discharge are discussed in Section 3.2.6), and a relationship of best-fit was then found. The best-fit relationship was found to be a power curve for the rivers of the Umiat study, and was fit with quite high R^2 values. The equation of this power curve was then able to predict the SSC value at any discharge within a specific range.

3.2.4 Suspended Sediment Discharge

Suspended sediment discharge (q_s) is a frequent value of the total suspended sediment being transported over a specific period of time. q_s is defined as suspend sediment concentration multiplied by discharge at the same point in time. The value used for SSC was taken in this case from the generated suspended sediment rating curves developed above, while discharge was taken from the 15-minute discharge record available for the flow period on each river. The method that was used to develop this discharge record is discussed in Section 3.2.6. Finally, the values for q_s were calculated at 15-minute intervals for the entire flow season, and these values were then used to calculate the annual suspended sediment load.

3.2.5 Turbidity

Campbell Scientific OBS-3+ turbidity sensors were installed at the Anaktuvuk, Chandler and Itkillik on July 10, 2011. These sensors have optics on the side of the body; installation involved mounting the sensor on rebar driven into the streambed, with the optics facing the middle of the channel and 180° away from the rebar. The sensor was installed roughly 15 centimeters above the channel bed on all three rivers, and in close proximity to the intake of the Isco sampler. Each turbidity sensor was wired into Water and Environmental Research Center (WERC) operated surface-water observation stations at each river; data was then transmitted via radio telemetry, with the sensors taking a reading every fifteen minutes. The OBS-3+ sensors operated at a wavelength of 850 nanometers (±5 nm) and were capable of measuring turbidity levels from 0 to 4000 NTUs (nephelometric turbidity units). Accuracy of turbidity readings was 2% or 0.5 NTU, whichever was greater (Campbell Scientific 2008). For the summer of 2012 Campbell Scientific Hydro Wipers for the optical windows were also installed to reduce the buildup of organic matter and other debris on the sensor.

3.2.6 Discharge Measurements

Discharge measurements were made using an acoustic Doppler current profiler (ADCP), which was mounted to a zodiac or inflatable kayak. The boat was slowly driven across the river in a transect to make a measurement; typically at least four transects were conducted at one time and the average discharge was calculated from these measurements. The coefficient of variation between the four measurements was typically less than 5%, otherwise more transects were made (Mueller and Wagner 2009). The exact ADCP used was dependent on discharge; an RDI Rio Grande 1200 kHz was used at maximum channel depths greater than five meters, while an RDI StreamPro 2000 kHz was used for maximum depths less than five meters. Water levels were monitored using HOBO U20 water level pressure transducers, as well as Instrumentation Northwest Aquistar PT12 (SDI12) pressure transducers. These pressure transducers recorded a measurement of water depth above the sensor every 15 minutes, which was then compared against manual water level measurements to ensure sensors were not moving in the water. This was not a frequent event, but something that it was important to consider. In addition surveys were conducted throughout the flow season to correlate water surface elevations to established benchmarks and to verify pressure transducer data. Finally a stage-discharge relationship was created using the data from both the discharge measurements and the 15-minute pressure transducers measurements. To create this rating curve, the measurements were plotted and a line of best-fit was plotted through the points. While the rating curve was valid for a range of discharges, it was not valid for conditions over bankfull (Kane et al. 2012).

3.2.7 Climate Data Collection

A network of climate data stations were operated throughout watersheds of the Umiat Corridor study area. Most of these stations collected weather data. At the gauging sites on each river, a water station collected meteorological data, as well as data on water levels, stream temperature, turbidity etc. In the Chandler watershed three stations were located in the upper basin, two in the mid-basin and one at the gauging site (Figure 3.6). In the Anaktuvuk River watershed there were two meteorological stations in the upper watershed, two in the mid watershed and one at the gauging site. Finally, the Itkillik River watershed had the sparsest of data collection, with meteorological data only collected at the gauging site. There are however stations on both sides of the Itkillik watershed, which is a narrower watershed (Kane et al. 2012).

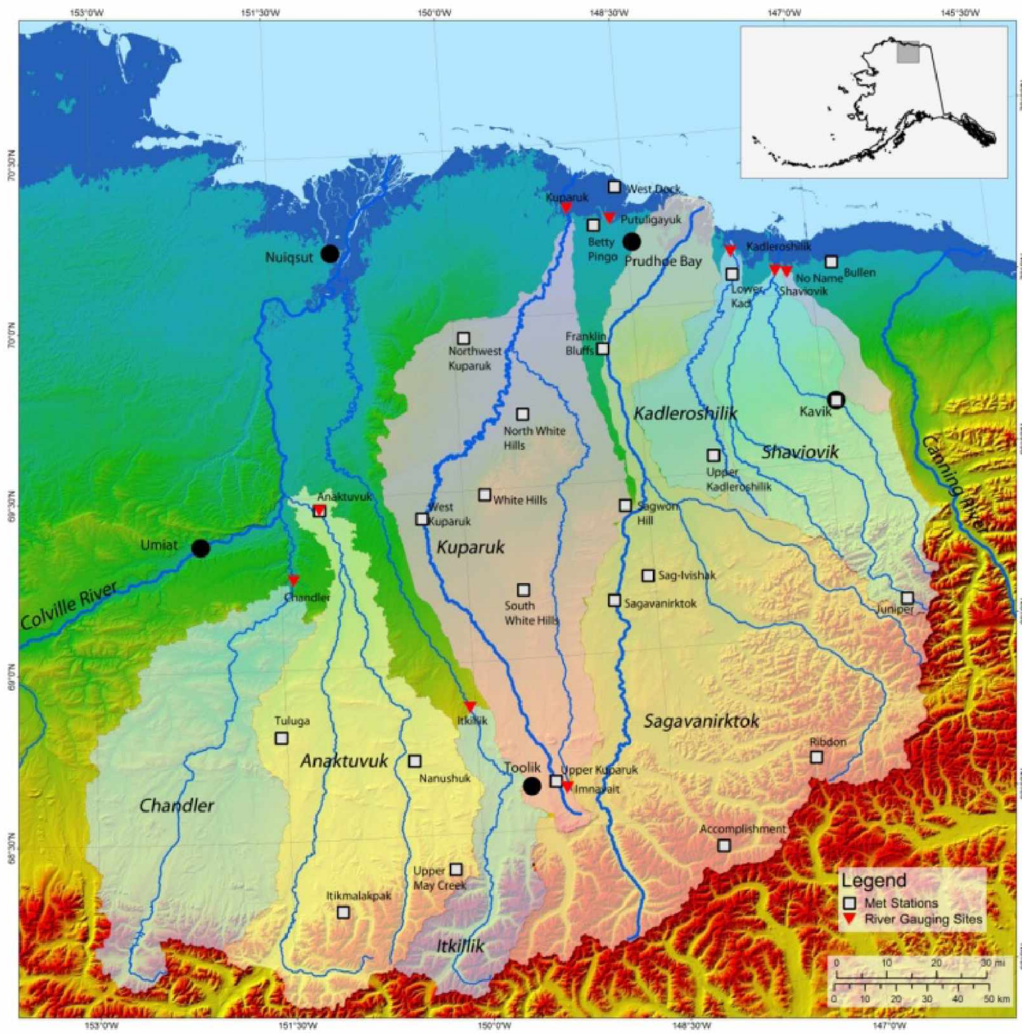

Figure 3.6 Map of meteorological stations and river gauging sites of the Umiat Corridor Hydrology Project.

The meteorological stations were operated at the Anaktuvuk, Chandler and Itkillik Rivers year round. On the Anaktuvuk and the Itkillik Rivers the meteorological station (gauging stations) also monitored water levels and turbidity; on the Chandler River, the meteorological station was 2 kilometers upstream of the gauging station. Air temperature and relative humidity were measured at 2 meter height using Campbell Scientific HMP45C Temperature Relative Humidity Sensors. Net radiation was measured with a Kipp and Zonen NR-Lite Net Radiometer, at a height of 1.5 meters. A Texas Electronics 525WS or 525MM tipping bucket measured summer precipitation. Wind speed and direction were measured with a RM Young 05103 anemometer at 3 meter height. Near surface soil moisture was observed with Campbell Scientific CS616 TDR sensors, while soil temperature was measured with YSI thermistors at incremental depths. Finally, snow depth was measured using a Campbell Scientific Sonic Ranger SR50 or SR50A. In addition to the sonic sensors, snow surveys to measure snow depth and density were conducted each spring over an area of 25 m by 25 m. Data collected at the meteorological and water monitoring stations were recorded by Campbell Scientific CR1000 loggers.

3.3 Results

3.3.1 Hydrometeorological Conditions in 2011 and 2012

3.3.1.1 Snow

The end of winter snow depth and snow water equivalent (SWE) were measured at multiple sites throughout each watershed, and then the basin average was calculated (Table 3.2) for 2011 and 2012 (Stuefer et al. 2011; Stuefer et al. 2012). In 2011 the Chandler River had the largest SWE of the three studied watersheds, while the Anaktuvuk had the lowest. As previously discussed, end of winter SWE can be a very important factor in the total suspended sediment yield of a river during spring breakup because it provides the main water input to the generation of runoff to the rivers during this time. Inter-annual comparisons cannot be made at this time as SSC was not measured during breakup in 2012, but as discussed later (Section 3.3.3.3), the

Anaktuvuk River did have the lowest peak in SSC in 2011 during spring melt, while the Chandler River peaked at the highest value of SSC.

Table 3.2 End of winter average SWE [mm] for the Anaktuvuk, Chandler and Itkillik River watersheds in 2011 and 2012.

Year / SWE [mm]	2011	2012
Anaktuvuk River (basin average)	76	80
Chandler River (basin average)	104	116
Itkillik River (basin average)	87	60

3.3.1.2 Summer Precipitation

While much of the precipitation that occurs on the North Slope of Alaska falls during the long winter as snow, summer precipitation can still have a strong effect on the hydrologic and sedimentologic regimes of a river (McNamara et al. 1998; Kane et al. 2003) . Table 3.3 shows the summer precipitation totals for the Anaktuvuk and Chandler River stations. Summer was considered the period between June 1st and September 15th. The Chandler River gauge site had almost double the precipitation in the summer of 2012 compared to the summer of 2011, while the Anaktuvuk River gauge site had an increase of 27%. Precipitation data was not collected at any location within the Itkillik River watershed.

Table 3.3 Summer precipitation totals [mm] for the Anaktuvuk and Chandler gauging sites.

Year / Rainfall [mm]	2011	2012
Anaktuvuk River (gauge site)	107	145
Chandler River (gauge site)	66	130

While the total precipitation that falls as rain is a factor in sediment transport, each watershed responds differently to these rain events. The summer rainfall and river discharge for the

Anaktuvuk River are shown in Figure 3.7 (this graph does not include the peak discharges of spring breakup, the scale for discharge goes to 350 m^3/s). As was quite evident in 2011, large summer rainfall events did not have a large corresponding increase in discharge in comparison to the peak caused by spring breakup. It is important to consider whether these rain events were localized events or occurred throughout the entire watershed; in comparison to snowmelt which involves the entire watershed, rainfall events in large watersheds rarely encompass the entire basin. A large precipitation event with little change in discharge indicates that the precipitation was a localized event, or that it occurred into a watershed with dry antecedent moisture conditions, where most of the rainfall was stored as supra-permafrost groundwater in the active layer. On 7/16/2011 there was a rain event at the Anaktuvuk River gauge site of 16 millimeters, which caused minimal change in discharge, although it did come after a rain event of longer duration but lower intensity. The rain event that began on 8/31/2012 lasted for almost a week, and although no intensity exceeded 0.5 mm/hour, there was a sizeable rise in discharge.

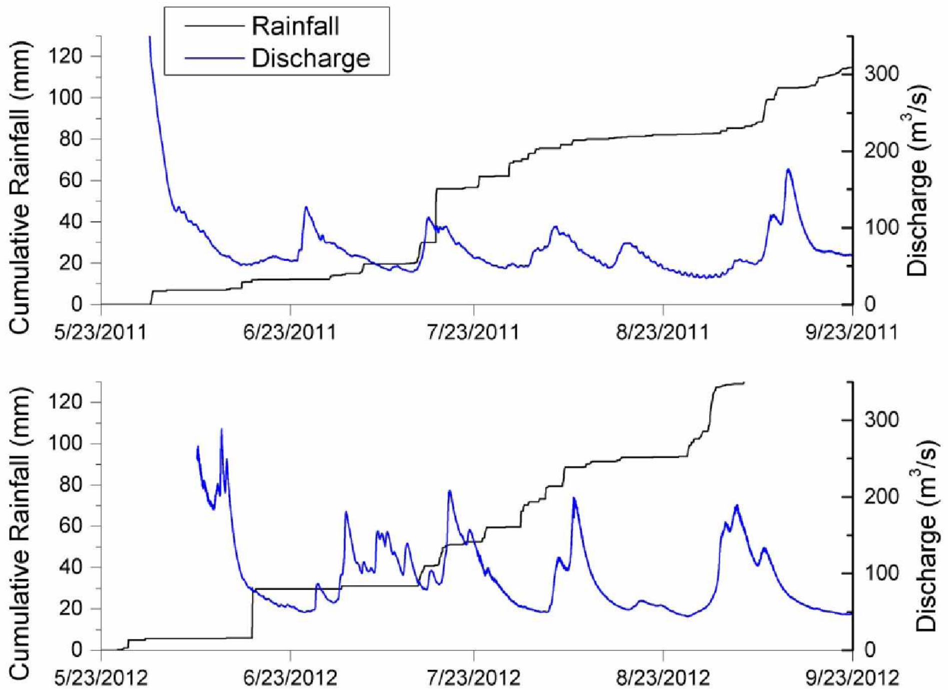

Figure 3.7 Cumulative rainfall and discharge for the Anaktuvuk River in 2011 and 2012.

The response of the Chandler River to summer rain events can be seen in Figure 3.8. As indicated in Figure 3.8, the discharge response to summer precipitation appeared to be higher in 2012 compared to 2011. One possible explanation for this was that in 2012 the groundwater storage was maximized early in the summer season, causing summer rain events to not be stored in the groundwater system and to cause large increases in the hydrograph as a result. In arctic watersheds the groundwater storage system is comprised of the active layer, with water stored in this zone known as supra-permafrost groundwater. The increased hydrograph response in 2012 may also be due to rain events that involved a greater percentage of the watershed than in 2011. In 2012 there were large peaks in the hydrograph (example on 7/5/2012), even though Chandler River gauge site did not experience any precipitation at the time of the increased discharge. If a meteorological station high in the mountains is considered, however, the large peak in the Chandler River hydrograph is explained. White Lake meteorological station was in the mountains of the Chandler watershed, and experienced an intense and prolonged rain event in early June (Figure 3.9). In addition, the Anaktuvuk River gauge site received more rain in both 2011 and 2012 (Figure 3.10), but with White Lake meteorological station receiving the most rain of these three sites.

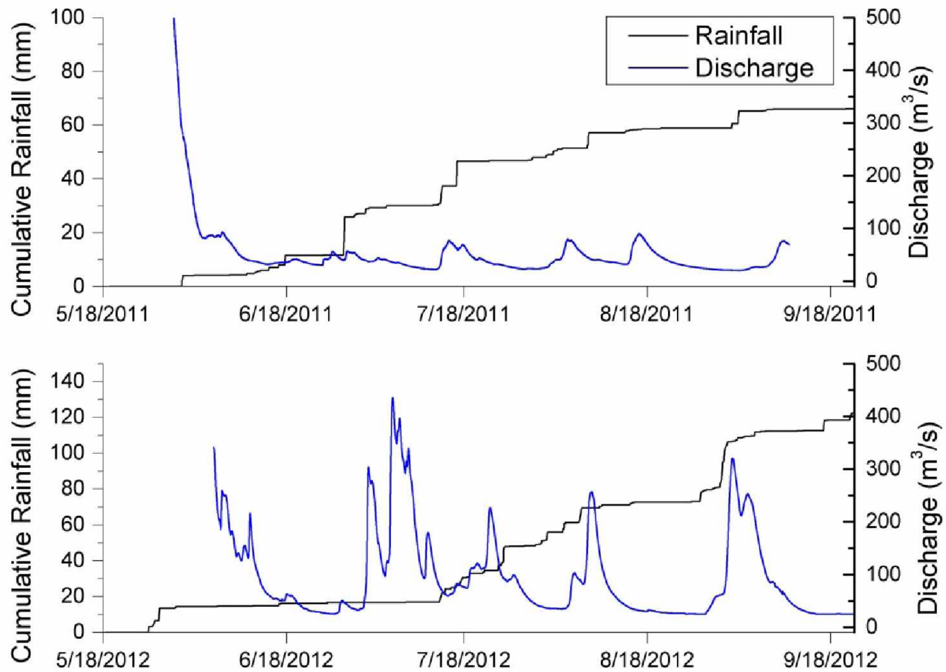

Figure 3.8 Cumulative rainfall and discharge for the Chandler River in 2011 and 2012.

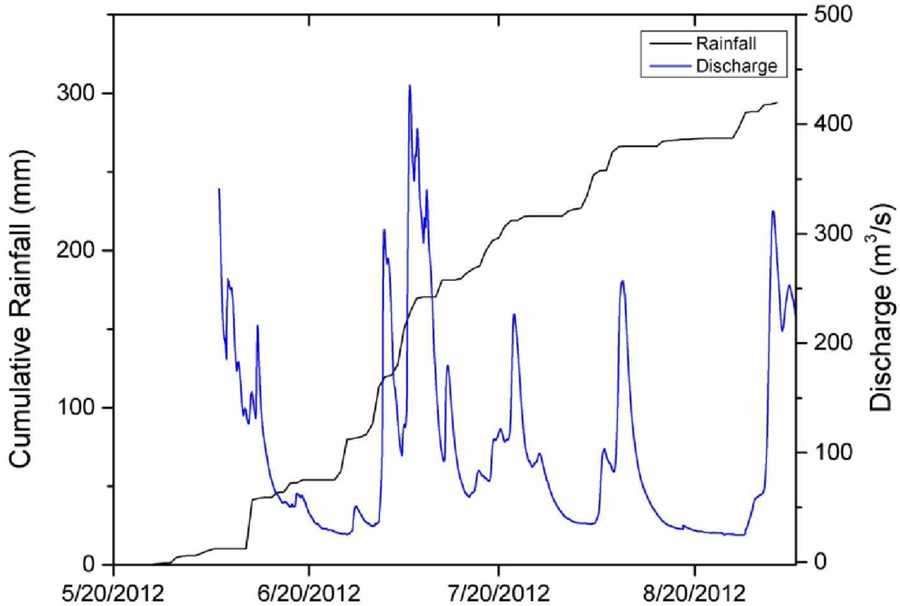

Figure 3.9 White Lake meteorological station cumulative rainfall and Chandler River discharge for 2012.

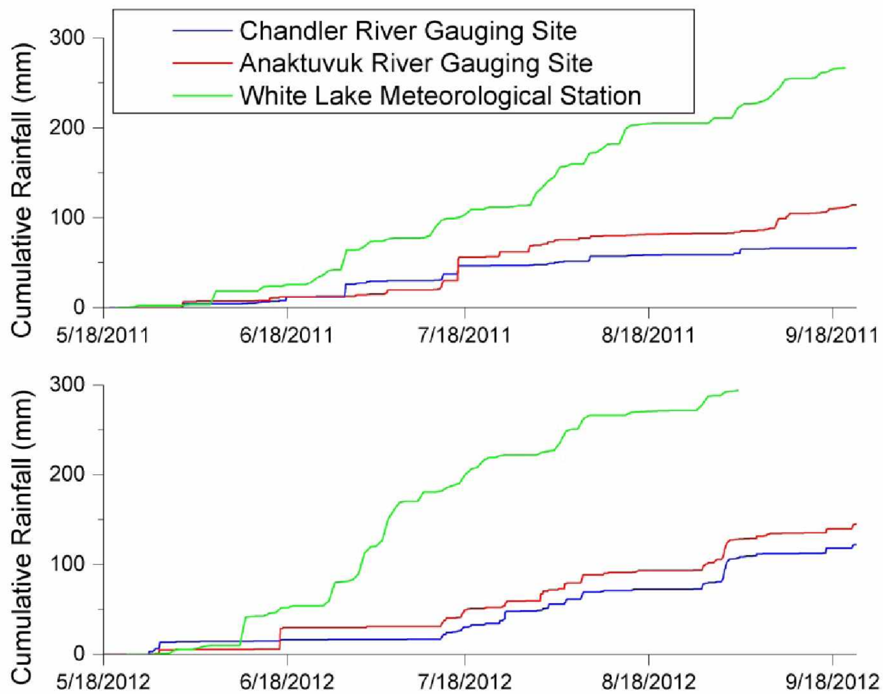

Figure 3.10 Cumulative rainfall for the Chandler, Anaktuvuk and White Lake stations, for 2011 and 2012.

3.3.2 Bed Sediment Grain-Size Distribution

The bed sediment grain-size distribution is presented in Figure 3.11. The D_{50} (the median grain size, of which 50% of grains are smaller) for each river is presented in Table 3.4. The D_{50} was 35.8 mm on the Anaktuvuk River at the gauging site, equivalent to coarse gravel; on the Chandler River near the gauging site the D_{50} ranged between 27.1 millimeters and 41.5 millimeters (coarse gravel and very coarse gravel). The Itkillik River gauging site had the largest D_{50} of 65 millimeters; this is very large gravel, bordering on small cobbles (Table 3.4). On the Chandler River two values are presented for the D_{50}; this is due to the large variation that exists in bed sediments. Both of these bed sediment distributions were measured on the same gravel bar, highlighting the need for increased sampling. The grid with the larger D_{50} was referred to as the Chandler coarse grid, while the other was the Chandler fine grid.

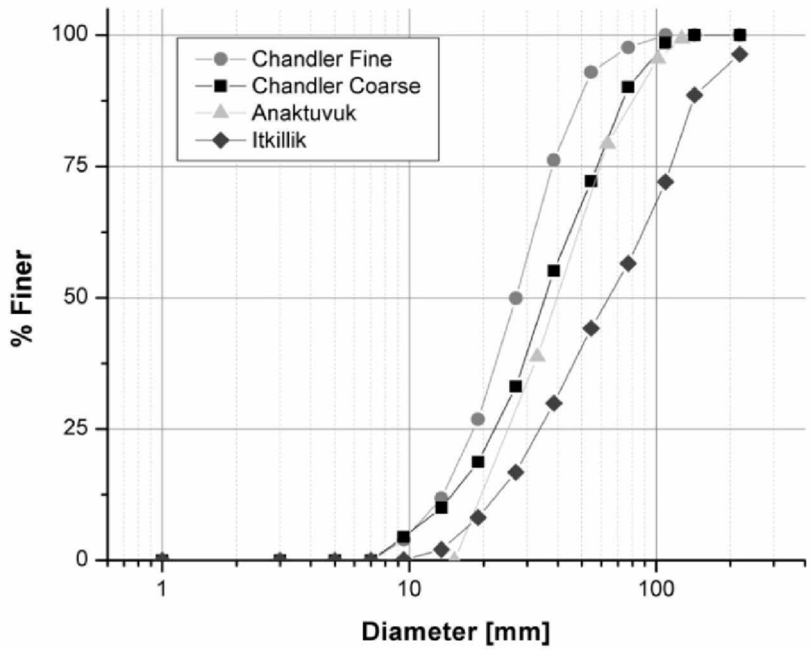

Figure 3.11 Bed sediment grain-size distribution for the Anaktuvuk, Chandler and Itkillik Rivers.

Table 3.4 D_{50} [mm]of the bed sediments for the Anaktuvuk, Chandler and Itkillik Rivers at the gauging sites.

	D_{50} [mm]
Anaktuvuk River	35.8
Chandler River [fine]	27.1
Chandler River [coarse]	41.5
Itkillik River	65.0

3.3.3 Suspended Sediments

3.3.3.1 Correlation between Isco and Depth-Integrated Samples

A comparison between SSC calculated from both the Isco sampler and the depth-integrated sampler is shown for the Anaktuvuk River in Figure 3.12. The relationship was linear, with the Isco always over-predicting SSC when compared to the depth-integrated sampler. The Isco sampler intakes, while not usually on the bed itself, were in the lower portions of the water column. As most suspended sediments are carried at roughly 60% of the water depth (Garcia 2008), the relatively low location in the water column of the Isco intake led to an over-prediction of SSC when compared to a depth integrated sample. On the Chandler River (Figure 3.12) the Isco sampler usually over-predicted the SSC value as well, but in a few instances the depth-integrated sampler did have a higher SSC value than the concurrent Isco sample at times of low-flow. The most likely reason for this is that the intake for the Isco sampler was quite close to the bank, and thereby sampling from a section of river that was not carrying as much sediment as the main channel. Although it was assumed that SSC was constant across the river channel, it is possible that at these low flows the Isco was sampling from a backwater or an eddy with a lower SSC than the main current. With the high R^2 values present for both rivers, it is clear that the relationship between the point Isco samples and the depth-integrated samples is an accurate method for evaluating SSC throughout the entire river cross-section and throughout time. No curve is presented for the Itkillik River at this time due to an insufficient number of depth integrated samples. This lack of data makes it more difficult to analyze suspended sediment transport on the Itkillik River, as well as between all three rivers, but as Isco samplers were also installed on the Itkillik River some analysis was performed.

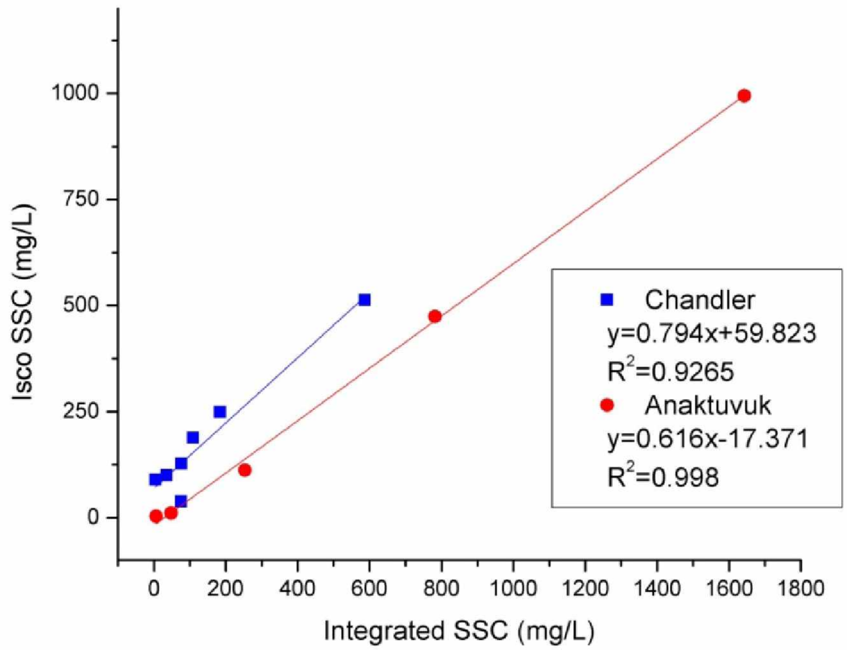

Figure 3.12 Relationship between Isco samples and depth-integrated samples on the Chandler and Anaktuvuk Rivers.

3.3.3.2 Suspended Sediment Rating Curves

Rating curves were produced for the Anaktuvuk and Chandler Rivers, relating SSC and discharge (Figure 3.13). These rating curves do not consider periods of time when the channel was ice-affected; effectively, they are accurate for flows that occur after spring breakup. The suspended-sediment rating curves developed for the Anaktuvuk and Chandler Rivers were completed using depth-integrated samples; again, due to a lack of depth-integrated samples on the Itkillik River a suspended sediment rating curve has not yet been developed. Considering the rating curves shown in Figure 3.13, it is clear that the Chandler River carried a larger suspended sediment load than the Anaktuvuk River for the same discharge. As well, the exponent of the power function is larger for the Chandler River, which indicates that for the same increase in discharge, the Chandler will show a larger increase in SSC than the Anaktuvuk.

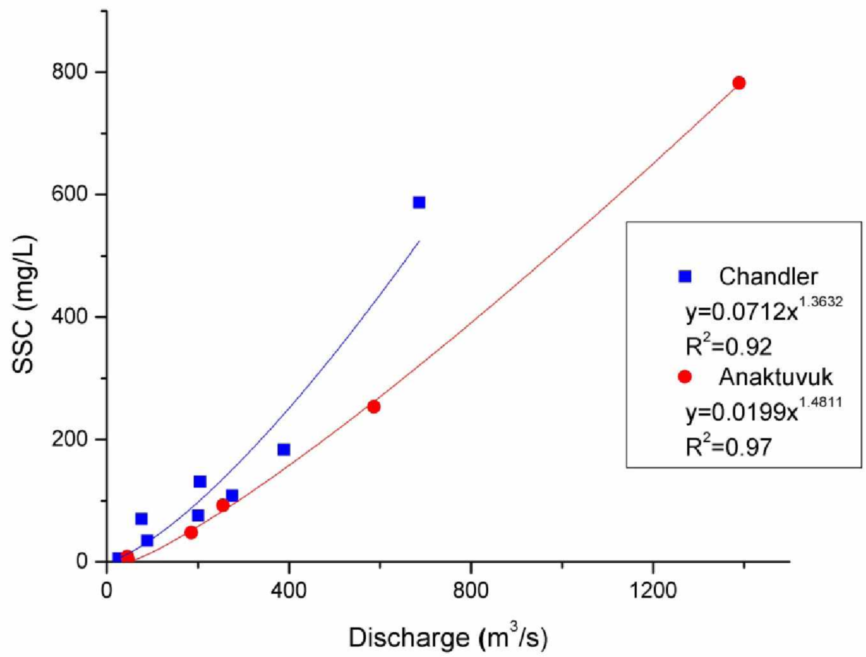

Figure 3.13 Suspended sediment rating curves for the Chandler and Anaktuvuk Rivers.

3.3.3.3 SSC and Discharge for 2011 and 2012

By plotting the SSC of the Isco samples and discharge throughout the summer flow season a picture of suspended sediment transport over time can be found. Considering the Anaktuvuk River (Figure 3.14), in 2011 SSC started quite low and then rose dramatically to a high value of 994.8 mg/L on 5/25/2011 at 12:40 AST. This rise in SSC corresponded to the lifting of some bottom ice and the erosion of snow in the river channel, exposing sediments and allowing for the dramatic rise in sediment transport. Over the summers of 2011 and 2012 it is clear that the majority of sediment transport on the Anaktuvuk River occurred during spring melt, and that summer storms caused little additional change in discharge or SSC. The inset graph of Figure 3.14 shows SSC for the summer months; there are clearly fluctuations in SSC in the summer that correspond to discharge, simply on a much smaller scale than when the flow season is considered as a whole. For the purpose of this study, summer was again considered to be the period of June 1 through September 15. For the recorded summer periods, SSC peaked in 2011 on 7/24/2011 at 35.7 mg/L, while in 2012 SSC rose to 88.9 mg/L on 6/12/2012.

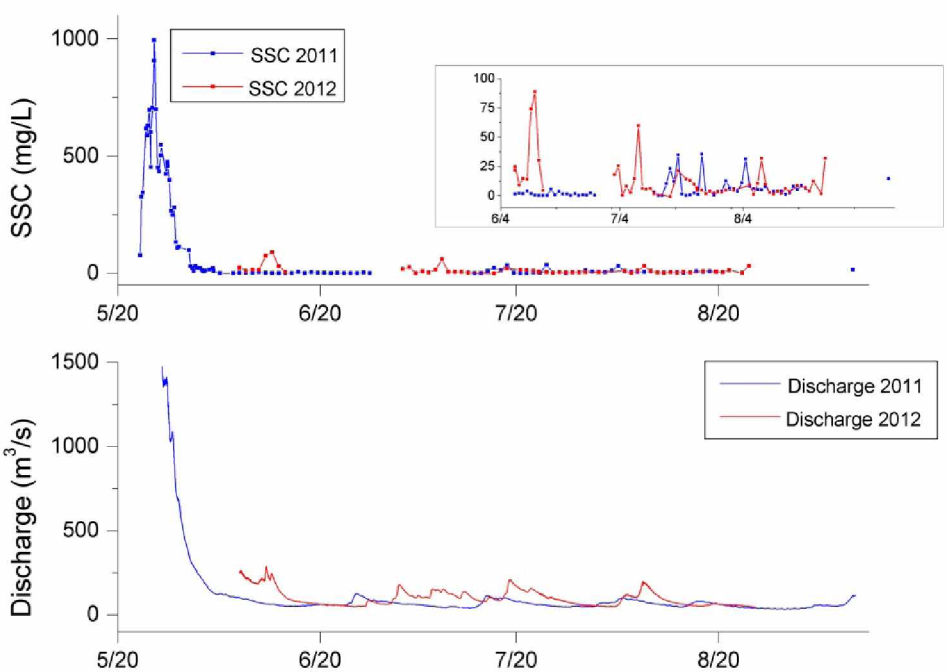

Figure 3.14 SSC (Isco) and Q for the Anaktuvuk River for 2011 and 2012.

On the Chandler River there were also large fluctuations in SSC and discharge during spring breakup, as well as during the summer (Figure 3.15). As with the Anaktuvuk River, in 2011 the water started flowing with essentially no sediments entrained, and then SSC quickly rose and peaked on 5/26/2011 at 15:00 at 2193.2 mg/L. The Chandler River experienced larger increases in SSC than the Anaktuvuk River for the same increase in discharge (Figure 3.13), as well as having a hydrograph that appears to respond more strongly to summer precipitation events based on the limited data available. Considering only the gauging sites (a full study should consider all the meteorological stations throughout both watersheds) , the Anaktuvuk River gauging site received more rain throughout almost all of the summer of both 2011 and 2012 than the Chandler River gauging site. This was especially clear in 2012 when a rain event in June caused an increase in the hydrograph and a rise of SSC to 1203.6 on 7/7/2012 mg/L; the largest SSC recorded in the summer of 2011 was 457.6 mg/L on 8/5/2011.

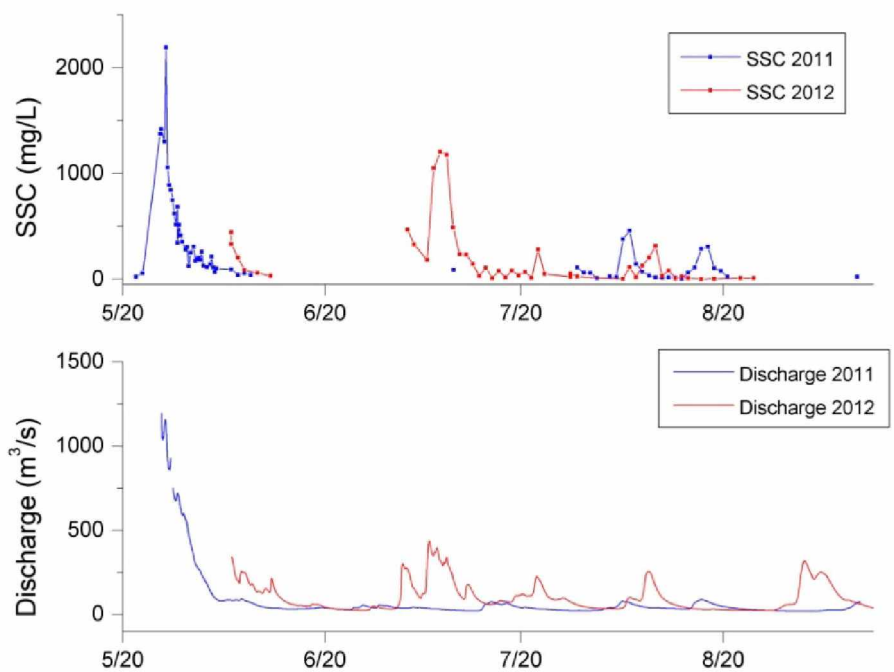

Figure 3.15 SSC (Isco) and Q for the Chandler River for 2011 and 2012.

The Itkillik River clearly had a suspended sediment transport regime that responded strongly to increases in discharge, as well as a “flashy” hydrograph that responded to summer precipitation events (Figure 3.16) The narrow shape of the Itkillik watershed, as well as its smaller size, makes it respond more intensely to summer precipitation events. The smaller size of the watershed means that a rain event affects a larger percentage of the watershed than a similarly sized event over a larger watershed. The highest value of SSC recorded on any river was on the Itkillik River on 6/8/2012, most likely due to the spring freshet. It is however possible that this high value was caused by a combination of the spring freshet and a rain event; 6.9 cm of rain fell at the May Creek station on 6/3/2012. This 6/8/2012 SSC value of 3947.7 mg/L is dramatically higher than any value recorded during breakup or the summer on the Anaktuvuk and Chandler Rivers, indicating that the Itkillik River has abundant sources of sediment that are easily accessed by relatively minor increases in discharge. The increase in SSC from 6/4/2012 to 6/8/2012 was an increase of 3772.8 mg/L, or 2100%. The discharge, on the other hand, increased by 37.5%. The presence of intermediate SSC samples on both the rising and falling limbs of the hydrograph for this rain event confirms that the exceptionally high SSC measured on 6/8/2012 is most likely accurate. This pattern is seen again throughout the summers of 2011 and 2012, as summer rain events cause increases in discharge and large changes in SSC.

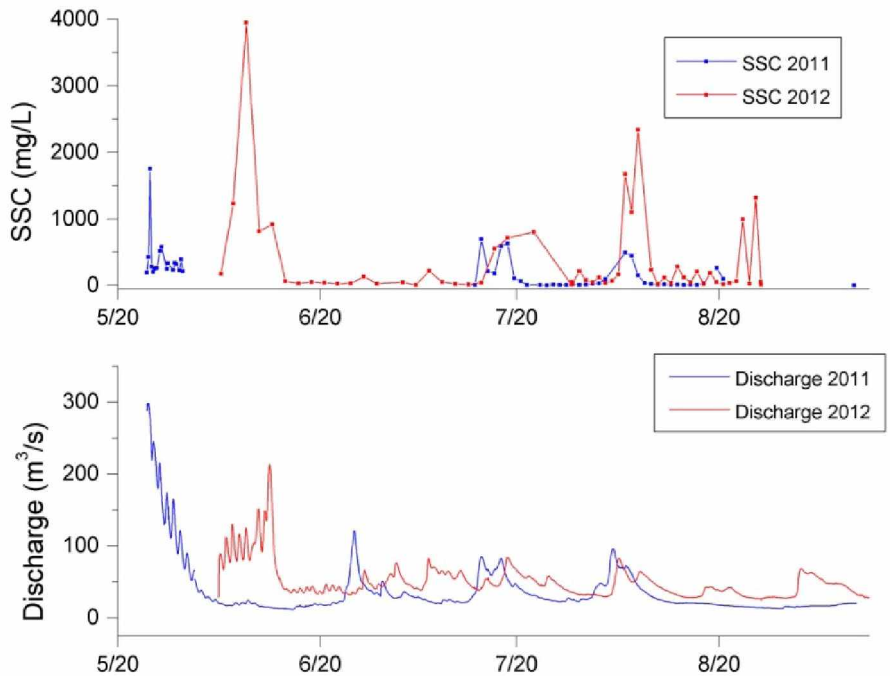

Figure 3.16 SSC (Isco) and Q for the Itkillik River for 2011 and 2012.

3.3.3.4 Turbidity

Turbidimeters were used as a surrogate for continuous, remote estimation of SSC. Installed in July 2011, results varied between rivers and over time. While it is clear that turbidity should relate strongly to SSC, in practice this is more complex. The Anaktuvuk and Chandler Rivers in particular carry organic material as well as suspended sediments, and in 2011 this organic material caused inaccurate readings on the turbidimeters because wipers were not installed on the instruments originally. This is especially clear on the Anaktuvuk River (Figure 3.17), where we see turbidity rising rapidly in late-August despite a declining discharge. This is a clear indication that the turbidimeter is not reading correctly. The Chandler (Figure 3.18) and Itkillik (Figure 3.19) Rivers had fewer issues with fouling in 2011 than the Anaktuvuk River. For the summer of 2012 the turbidimeters were installed with wipers on the optical windows to reduce the problems with organic matter.

Turbidity measurements on the Anaktuvuk River (Figure 3.17) were the least accurate of the three rivers. Fouling caused very poor readings in 2011, and in 2012 there were very large fluctuations in readings that make it difficult to clearly see patterns in the turbidity measurements. There is a clear response in turbidity to the increase in discharge on 6/11/2012, but the exact response to increases in discharge later in the summer is difficult to determine due to the large amount of background noise.

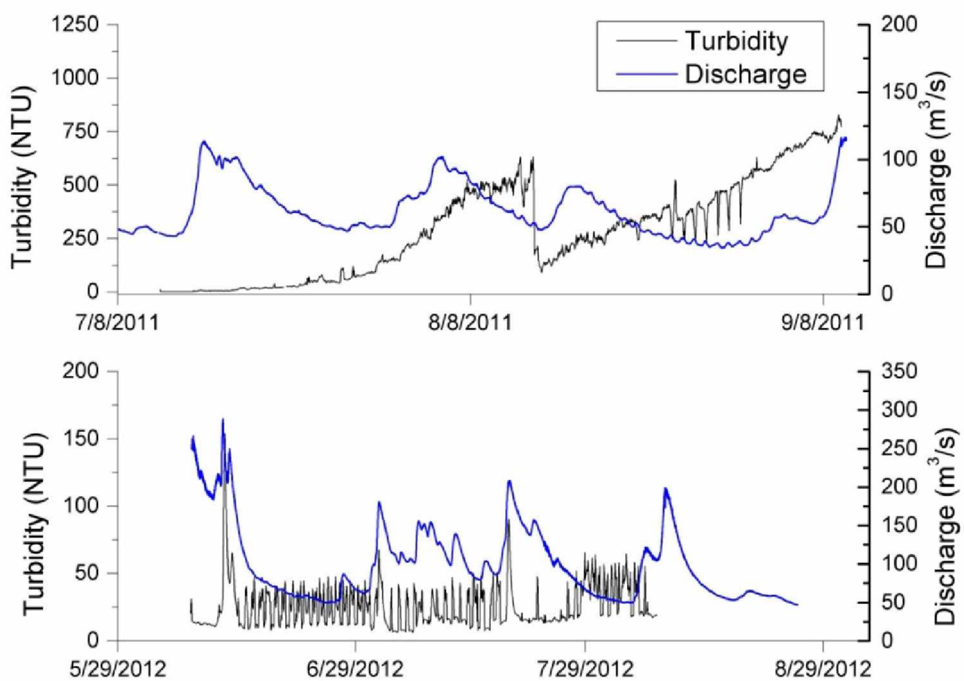

Figure 3.17 Turbidity on the Anaktuvuk River for 2011 and 2012.

Turbidity measurements on the Chandler River (Figure 3.18) are much clearer than those made on the Anaktuvuk River. Responses in turbidity are difficult to distinguish in 2011 prior to the installation of wipers, but in 2012 the Chandler River turbidimeters made clear measurements for the duration of the open water flow season. In July of 2012 there are very distinct increases in turbidity that correspond to increases in discharge on 7/1/2012, 7/5/2012, 7/11/2012 and 7/23/2012. For the event that occurred on 7/5/2012 there is an increase in discharge from 48.31 m^3/s to 134.5 m^3/s on 7/7/2012; the corresponding increase in turbidity is from 39.54 NTU to 1833 NTU.

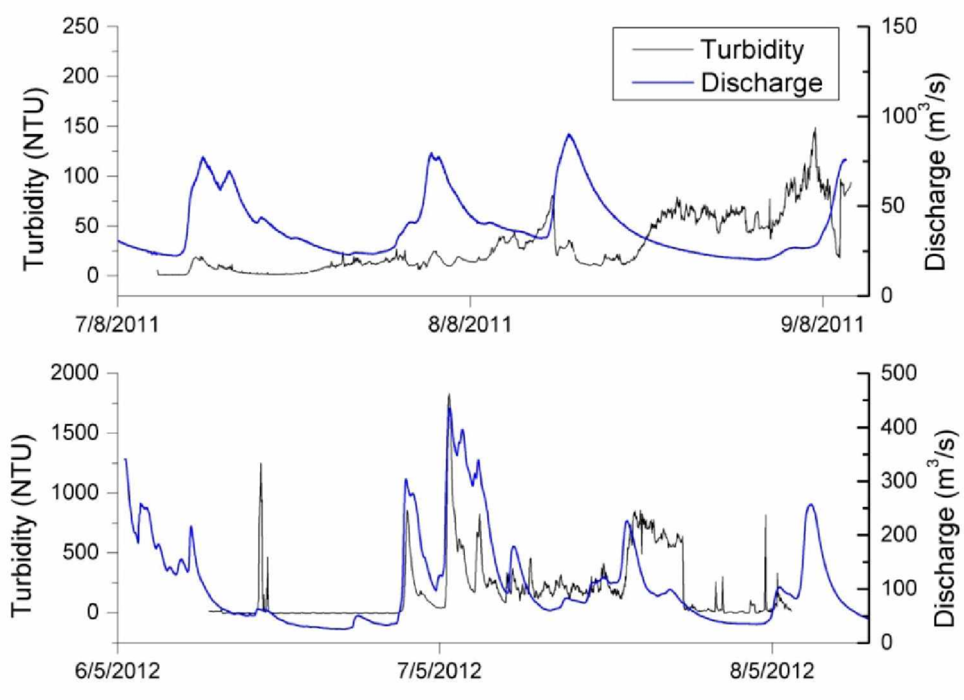

Figure 3.18 Turbidity on the Chandler River for 2011 and 2012.

On the Itkillik River there are clear turbidity measurements for 2011 and 2012 (Figure 3.19). Turbidity unmistakably rises when discharge does, and there is very little "noise" as is seen on the Anaktuvuk River. This is most likely due to the fact that the Itkillik River carries less organic matter than the Anaktuvuk River, and so the turbidimeter experiences less fouling.

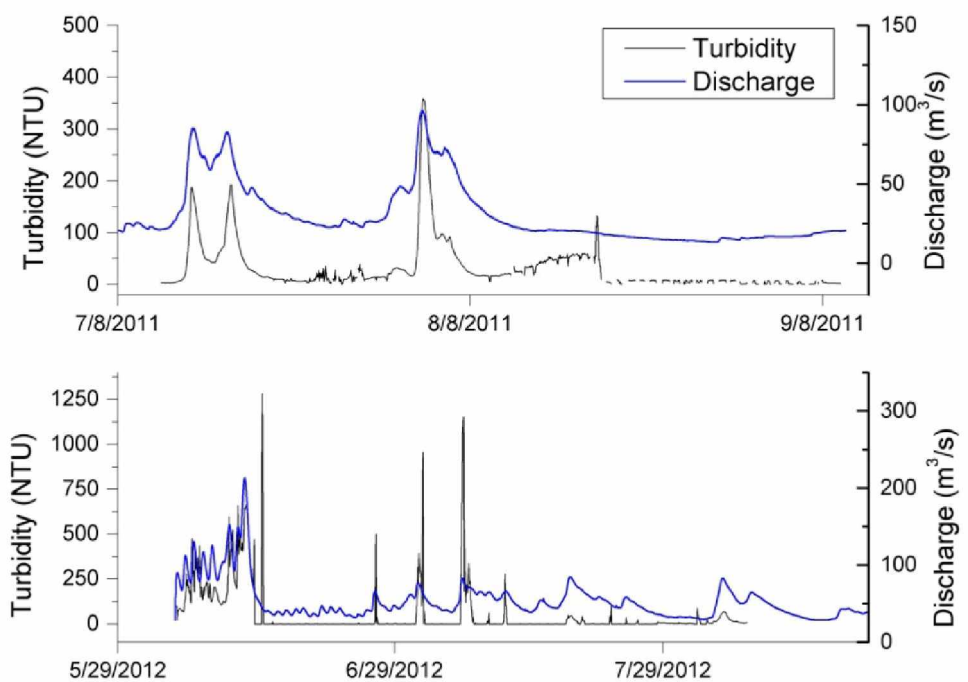

Figure 3.19 Turbidity on the Itkillik River for 2011 and 2012.

3.3.3.5 Suspended Sediment Discharge

While considering SSC at specific points in time conveys a large amount of information about the sediment transport regime of a river, insight is also provided by considering the suspended sediment discharge (q_s). This allows for the comparison of sediment loads between rivers of varying discharges, and within the same river over time as discharge fluctuates. Suspended sediment discharge curves were developed for the Anaktuvuk (Figure 3.20) and Chandler (Figure

3.21) Rivers using the suspended sediment rating curves developed from depth-integrated samples (Figure 3.13) and the values of discharge at 15-minute intervals (also developed using stage-discharge rating curves), during periods of flow when the channels were not ice affected. Comparing Figure 3.20 and Figure 3.21 it is shown that the Chandler River peaked at a higher q_s in 2011 than the Anaktuvuk River, despite the fact that the Anaktuvuk River peaks at a higher discharge (see Figure 3.14 and Figure 3.15).

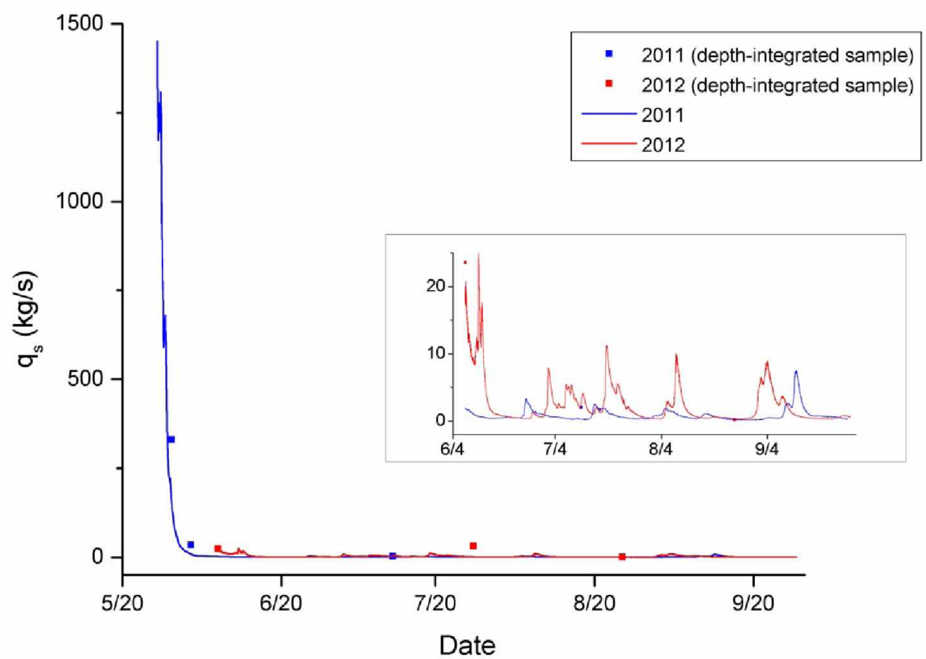

Figure 3.20 Anaktuvuk River estimated suspended sediment discharge for 2011 and 2012.

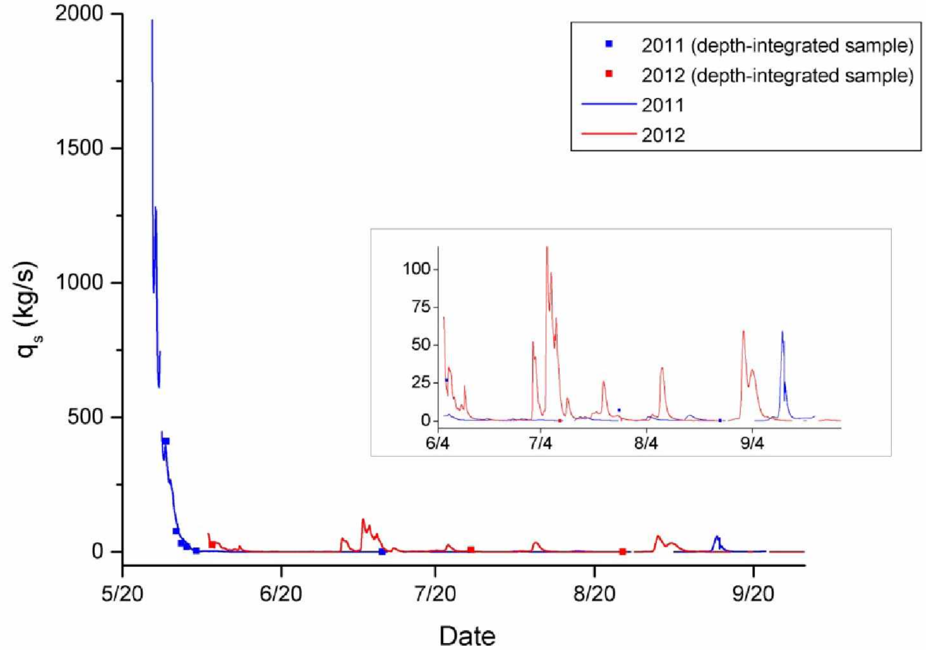

Figure 3.21 Chandler River estimated suspended sediment discharge for 2011 and 2012.

Considering Figure 3.20 and Figure 3.21 it is clear that most of the suspended sediment transport of the open water season occurred during the spring breakup for 2011. Looking at suspended sediment yields month-by-month makes it even more clear how big an event the spring melt is on rivers in the Alaskan arctic. On the Anaktuvuk River in 2011, 94% of suspended sediments were moved in the month of May (Table 3.5), which was actually a one week period at the very end of the month, from 5/26/2011 to 5/31/2011. On the Chandler River (Table 3.6) the spring melt moved 91% of suspended sediments in 2011, during the period of 5/25/2011 to 5/31/2011. If discharge is also considered for the entire flow season, on the Anaktuvuk River in 2011 approximately 31% of flow occurred during the month of May; on the Chandler River in 2011 39% of flow occurred in May. This indicates that the large volume of water flow during breakup is not enough alone to cause the large flux of suspended sediments. Along with the magnitude of spring melt, the other clear feature of the suspended sediment yields is the large inter-annual variability within both rivers. On the Anaktuvuk River in July, in 2012 there was a 333% increase over 2011 in q_s, while the Chandler River experienced an even larger increase between the two Julys. This variability is due to changing patterns of precipitation, in which the summer of 2012 was overall a wetter summer than 2011.

Table 3.5 Suspended sediment yields for the Anaktuvuk River in 2011 and 2012, in metric tonnes per month.

	2011	**2012**
May	179464	NOT RECORDED
June	4985	7686
July	1791	7770
August	1659	3213
September	2853	4614

Table 3.6 Suspended sediment yields for the Chandler River in 2011 and 2012, in metric tonnes per month.

	2011	**2012**
May	203519	NOT RECORDED
June	6799	12593
July	1252	40060
August	2037	7541
September	8950	15289

3.4 Discussion

3.4.1 Methods

Several problems occurred with the Isco samplers in the harsh environment that is the North Slope. It is unfeasible to suspend the intake at a constant height above the bed during breakup due to the debris and ice carried by the rivers, the frozen nature of the bed and the high water levels. Large gaps occurred in the data set in the early summer; the Chandler River Isco was disconnected from its battery, presumably by an animal, while the Itkillik River Isco tipped over during high flows. Limitations are also caused by the size of the Isco samplers; each sampler can hold a maximum of twenty-four samples, and visits cannot always be conducted at such frequency. To address the breaks in data two Iscos were deployed at each river in the summer of 2012, with each Isco taking a sample every forty-eight hours, staggered to have one sample per day. As a result, there can be 48 days of continuous data without a site visit, and if one sampler is disrupted the density of sampling will be reduced but a broad picture of sediment load can still be achieved.

By taking an average of two integrated samples per day during breakup with the integrated sampler, a representation of sediment load throughout the water column can be achieved. This also addresses the problem of the Isco hose being on the river bed during breakup, allowing for a comparison between the Isco and integrated samples. The high R^2 value of the correlation between the Isco samples and depth-integrated samples reinforces the relationship between the two sampling methods (Figure 3.12).

It is important to consider the aspect of bedload transport, especially during the times that the Isco hose is directly on the river bed. Although bedload transport is typically lower near the banks where the Isco intake is, it would be ideal in the future to have an estimate of bedload transport.

3.4.2 Hydrometeorological Influences on SSC

The harsh environment of the North Slope of Alaska has a clear and profound influence on the sediment transport regimes of these rivers. With snow on the ground for over seven months of the year, the total end of winter snowpack drives much of the spring transport of suspended sediments. When considering the basin averages of SWE for 2011 and 2012, 2012 had a higher SWE in the Chandler and Anaktuvuk River watersheds, but was lower in the Itkillik River watershed. Without any SSC data for the spring melt period of 2012 it is impossible to make any accurate comparisons between the two years.

Many other studies of sediment transport in arctic rivers have considered the effects of summer rainfall on arctic rivers. On the Anaktuvuk and Chandler Rivers we see that there is relatively little runoff response to summer storms when considered on a temporal scale that also includes spring melt. When the summer is considered separately, however, larger summer rain events can cause rises in discharge of 150%. This will have a corresponding rise in SSC, as can be seen in both the suspended sediment rating curves and the plots of SSC throughout 2011 and 2012. As with previous studies (Kane et al. 2003; Lewis et al. 2005; McNamara et al. 2008), the rivers studied for this thesis displayed a range of responses to summer rainfall events, with numerous factors contributing to the responses of the hydrograph and SSC. Antecedent moisture conditions, basin size, basin gradient and the specific storm characteristics (size, intensity, etc.) all contribute to the differing responses.

3.4.3 Suspended Sediment Transport

The assessment of suspended sediment transport began by creating suspended sediment discharge rating curves. Rating curves were developed for the Anaktuvuk and Chandler Rivers using data collected throughout the open water season. The high R^2 values indicates that there is a very close relation between discharge and SSC, and that rises in discharge are closely followed by rises in suspended sediment transport. This positive correlation between SSC and discharge has been corroborated by numerous other studies of suspended sediment transport in arctic rivers (Lewkowicz and Wolfe 1994; Bogen and Bonses 2003; Forbes and Lamoureux 2005). The high R^2 values of the power relationship between SSC and discharge on the Anaktuvuk (R^2=0.97) and Chandler (R^2=0.92) was also confirmed in these previous studies.

Available data indicates a very unique pattern of SSC in the very first hours and days of flow during spring melt on arctic rivers; flow starts extremely clear and with a negligible SSC, then as ice and snow erode from the channel and bottom-fast ice lifts, SSC rises dramatically and peaks at very high levels relatively shortly after flow has begun. As other studies have shown (Oatley 2002; Best et al. 2005), the presence of ice in the channel limits scour and thereby greatly reduces the sediments available for transport within the river channel.

3.4.4 Turbidity

Previous studies have compared SSC to turbidity, with the relationship typically being linear (Foster et al. 1992; Grayson et al. 1995; Lewis 1996; Lewis 2003; Lewis et al. 2005), with high R^2 values reported of 0.875 (Grayson et al. 1995) and 0.93 (Lewis et al. 2005) as examples. The relatively limited number of depth-integrated SSC samples makes it difficult to compare SSC and turbidity on the Itkillik River, which had the clearest turbidity measurements. On the Anaktuvuk and Chandler Rivers the high amount of fouling that occurred in 2011 and to some extent in 2012 also made a comparison between SSC and turbidity inaccurate. Future work should include more measurements and the correlation of SSC and turbidity.

4 National Petroleum Reserve – Alaska Hydrology Study

4.1 Study Sites

This project involved seven rivers (Table 4.1) that were located in the National Petroleum Reserve - Alaska (NPR-A) (Figure 4.1). This project was performed by personnel from both the Bureau of Land Management and the University of Alaska Fairbanks. Four rivers were considered only briefly; these were the Ublutuoch River, Ikpikpuk River, Judy Creek and Otuk Creek. The three other rivers that were studied in greater detail are Fish Creek, Prince Creek and Seabee Creek.

Table 4.1 Coordinates for gauge stations in the NPR-A.

	Latitude	Longitude
Fish Creek	70° 16.23’ N	151° 52.155’ W
Judy Creek	70° 13.241’ N	151° 50.13’ W
Ublutuoch River	70° 14.591’ N	151°17.823’ W
Ikpikpuk River	69° 46.008’ N	154° 39.825’ W
Seabee Creek	69° 22.29’ N	152° 09.47’ W
Prince Creek	69° 19.30’ N	152° 30.84’ W
Otuk Creek	68° 29.128’ N	155° 43.032’ W

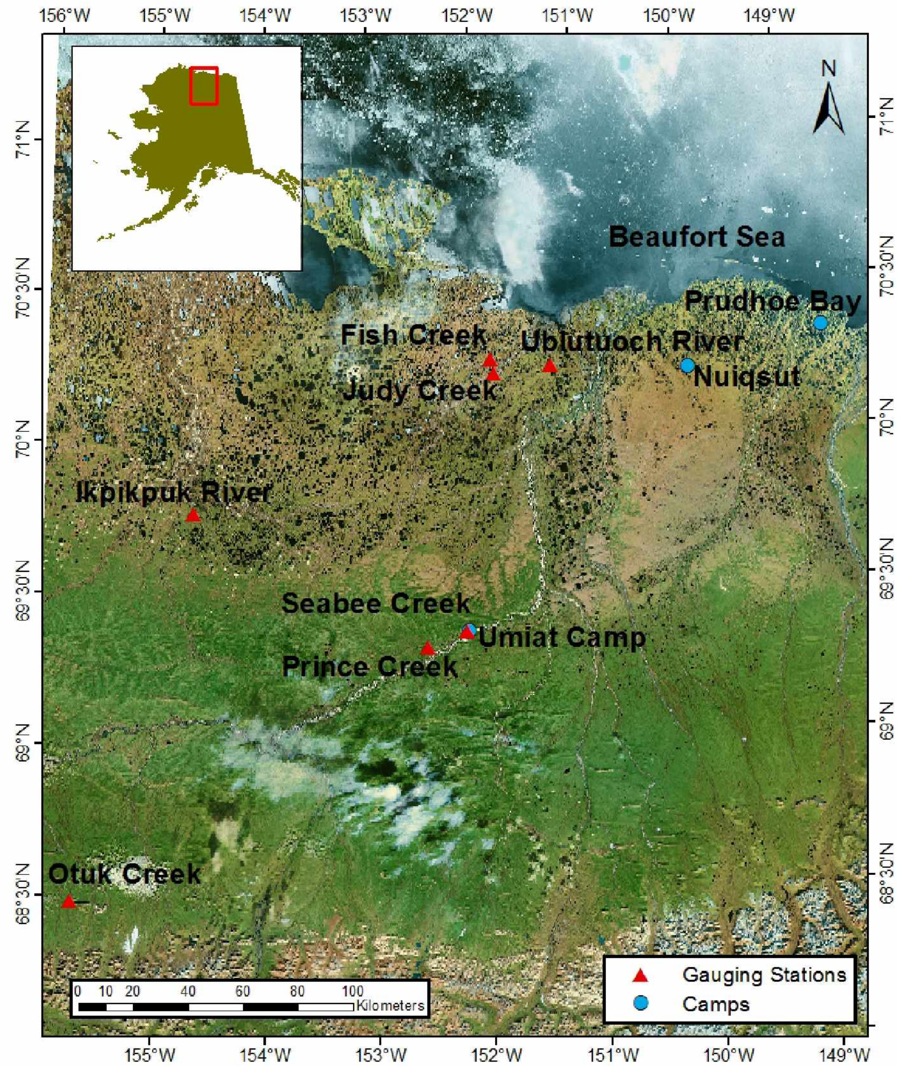

Figure 4.1 Map of study sites in the NPR-A study area.

4.2 Methods

4.2.1 Bed Sediment Distribution

To determine the bed sediment distribution at Prince Creek a photographic sampling method (Church et al. 1987) was used, as earlier discussed in Section 3.2.1.

4.2.2 Suspended Sediment Concentration

Samples were taken using two methods during this project. Grab samples were collected on all rivers, and this was the only method of collection on the Ikpikpuk River, Otuk Creek, Judy Creek and Ublutuoch River. For this method bottles were simply submerged near the bank until full. Automatic pump style samplers were deployed on Prince Creek, Fish Creek and Seabee Creek, allowing for more continuous monitoring of suspended sediment concentration in these three rivers. On Fish Creek and Seabee Creek Isco autosamplers were used; on Prince Creek a Sigma autosampler was used.

4.2.3 Discharge

Discharge was measured using several ADCPs depending on stream conditions. During spring breakup when water depths were greater, an RDI RioGrande was used in 2011 and an RDI RiverRay was used in 2012. During summer months when discharge and maximum depths were lower an RDI StreamPro ADCP was used. Two Pressure Systems KPSI pressure transducers were also deployed at each station, recording water levels at 15 minute intervals. The readings from these pressure transducers were used to develop a stage-discharge rating curve, similar to what was done for each river in the Umiat Project. In addition, air temperature was measured at each station. The loggers used were Waterlog with GEOS Satlink Transmitters.

4.3 Results

4.3.1 Bed Sediment Distribution

A bed sediment distribution was calculated for Prince Creek (Figure 4.2) using the method described in Section 4.2.1. The D_{50} was found to be 33.7 millimeters, which is on the small-end for very coarse gravel.

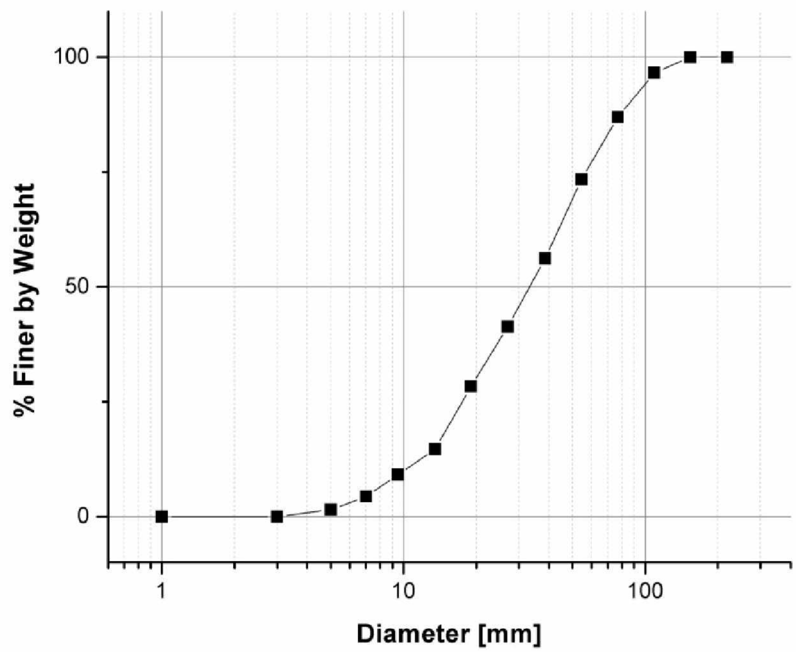

Figure 4.2 Bed sediment grain-size distribution for Prince Creek.

4.3.2 Suspended Sediment Concentration

SSC was monitored during spring breakup in both 2011 and 2012 on Seabee Creek, as well as throughout the rest of the open water season (Figure 4.3). In 2011 discharge peaked at 29.7 m^3/s on 5/27/2011, and in 2012 the peak was 18.9 m^3/s on 6/5/2012. SSC peaked at 134.6 mg/L on 6/9/2011, while in 2012 the peak in SSC corresponded to the peak in discharge at 12.2 mg/L on 6/7/2012. There were also peaks in SSC throughout the flow season in 2012, but overall values of SSC were much lower in 2012 than in 2011. The decrease in SSC that was related to spring breakup was 90% from 2011 to 2012.

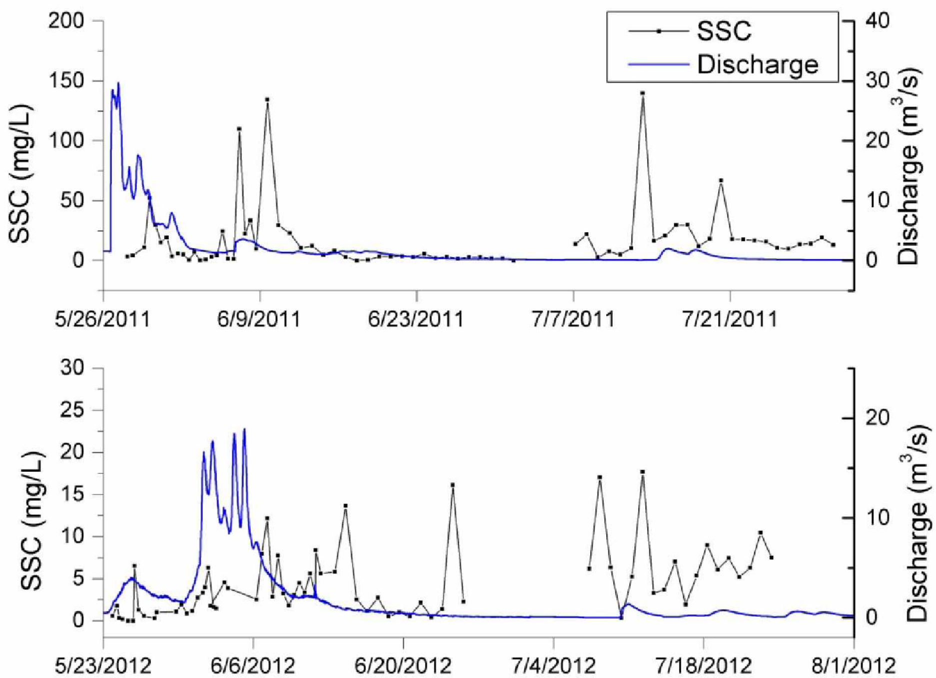

Figure 4.3 SSC (Isco) and Q for Seabee Creek for 2011 and 2012.

Spring breakup was captured in 2012 on Fish Creek (Figure 4.4) and discharge peaked on Fish Creek at 92.1 m^3/s on 6/6/2012. The corresponding rise in SSC was to a value of 184.3 mg/L on 6/6/2012; the overall peak in SSC came 14 days later on 6/20/2012 with an SSC of 267.4 mg/L. In 2011 only four samples were taken throughout the flow season, all via grab sample (Table 4.2). Of these the maximum SSC recorded was 96.8 mg/L on 6/7/2011. For reference, the peak in discharge in 2011 was 112.6 m^3/s on 6/3/2011.

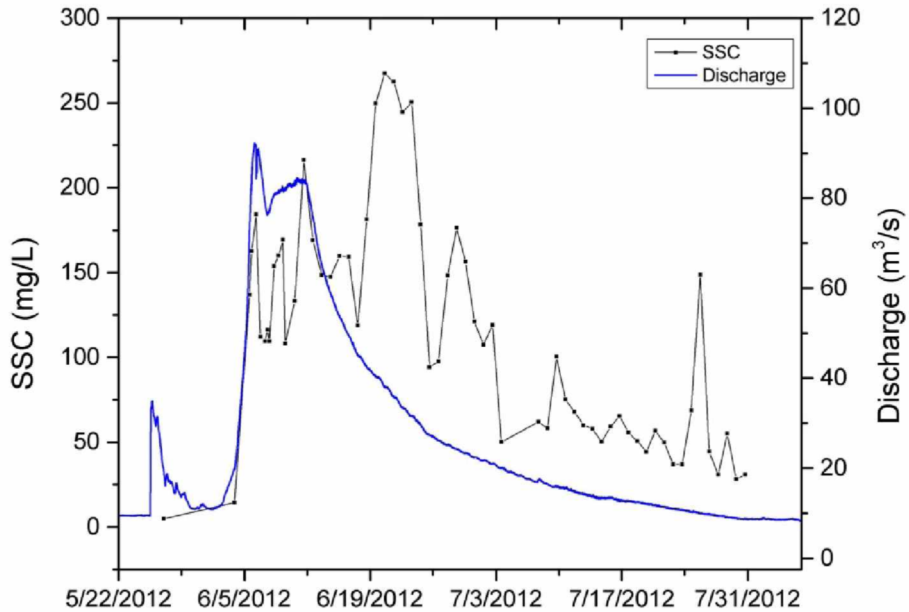

Figure 4.4 SSC (Isco) and Q for Fish Creek for 2012.

Table 4.2 Fish Creek SSC (grab) for 2011.

	SSC [mg/L]
6/2/2011	19.61
6/5/2011	39.10
6/7/2011	96.82
8/27/2011	14.61

Prince Creek had discharge and SSC measured for spring breakup in 2011 and 2012 (Figure 4.5). The peak in discharge in 2011 came on 5/29/2011 at 154.2 m^3/s, but SSC monitoring in 2011 did not begin until 6/6/2011. As a result the peak in SSC was most likely missed during spring breakup; the highest recorded values for SSC during this period was 140.2 mg/L on 6/9/2011, 170.6 mg/L on 7/11/2011 and the overall peak of 308.9 mg/L on 7/18/2011. In 2012 discharge peaked on 6/2/2012 at 138.8 m^3/s. The maximum SSC recorded was 3 days earlier on 5/31/2012 at a value of 777.4 mg/L.

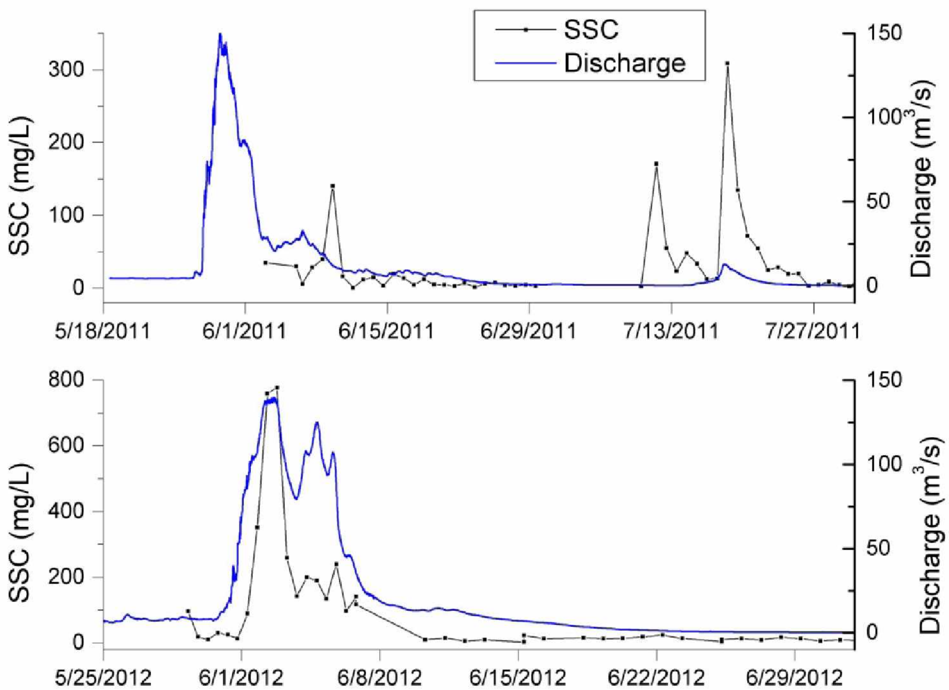

Figure 4.5 SSC (Isco) and Q for Prince Creek for 2011 and 2012.

Along with the measurements taken on Seabee, Prince and Fish Creeks, grab samples were taken sporadically on Judy Creek (Table 4.3), Ikpikpuk River (Table 4.4), Ublutuoch River (Table 4.5) and Otuk Creek (Table 4.6). Without consistent discharge and SSC measurements it is difficult to draw any conclusions about the suspended sediment transport regime of any of these rivers, but the measurements do give a general idea of what is occurring. Judy Creek (Table 4.3) has the highest SSC measurements of any of these 4 rivers, with a peak in 2012 of

1034.4 mg/L, which is many times greater than any other recorded peak in SSC in the NPR-A Rivers. The measurements taken 2 days before and 2 days after this extremely high value are also quite high, indicating that the SSC of 1034.4 mg/L is a reasonable measurement.

Table 4.3 Judy Creek SSC (grab) for 2011 and 2012.

	SSC [mg/L]
5/30/2011	6.44
6/3/2011	152.21
6/5/2011	196.39
6/7/2011	123.32
8/28/2011	0.19
5/27/2012	105.12
6/3/2012 16:00	466.88
6/5/2012 15:30	1034.36
6/7/2012 16:00	416.96
6/9/2012 15:00	145.87
9/1/2012 16:00	1.11
9/1/2012 18:00	1.59

Table 4.4 Ikpikpuk River SSC (grab) for 2011 and 2012.

	SSC [mg/L]
6/3/2011	72.67
8/26/2011	3.50
5/31/2012 17:00	85.01
6/4/2012	110.82
7/5/2012 17:10	1.58

Table 4.5 Ublutuoch River SSC (grab) for 2011 and 2012.

	SSC [mg/L]
6/5/2011	14.28
6/7/2011	13.74
6/8/2011	1.06
6/3/2012 19:40	0.85
6/7/2012 13:00	3.18
6/9/2012 11:30	15.97
6/15/2012 12:00	2.12
7/7/2012 12:30	0.89
9/1/2012 12:00	0.99

Table 4.6 Otuk Creek SSC (grab) for 2011 and 2012.

	SSC [mg/L]
6/4/2011	1.84
7/9/2011	0.52
5/28/2012 12:00	3.09
6/1/2012 18:30	26.71
7/6/2012 11:30	0.11
9/4/2012 14:30	0.00

4.4 Discussion

On Seabee Creek there was a very large change in SSC values during spring breakup between 2011 and 2012. Although there is limited data available for the rivers in the NPR-A, 2011 did have a short and very warm spring, while in 2012 temperatures increased and then decreased again. This resulted in a drawn-out melting of snow, and a lower peak in discharge, leading to a lower peak in SSC. Discharge peaked during spring breakup 36% lower than 2011 in 2012, while SSC dropped 90%. This highlights that the relationship between discharge and SSC is not a linear relationship, and that multiple years of data are needed to make a complete analysis of the suspended sediment transport regime of a river.

5 Discussion

Data collection efforts on the rivers in the NPR-A were much more limited than those on the Umiat project. As a result fewer conclusions can be drawn about the NPR-A data. While there is a clear relationship between discharge and SSC on the rivers in the NPR-A, it is not yet corroborated with suspended sediment rating curves. This may be due to the much smaller size of these rivers, which may have a more exaggerated response to small perturbations such as runoff from snow melt, small rain storms etc.

It is also interesting to look at the responses to spring melt among all the rivers. There are clear differences between watersheds of varying size, with larger watersheds typically having snowmelt runoff account for a larger percentage of annual runoff than smaller basins (McNamara et al. 1998). In addition to considering overall SWE, the trend of air temperatures in the spring is also important. If the end of winter SWE were identical for two years, but one had a strong, short warming period, and another had a very slow increase in temperatures there would clearly be a difference in the runoff response. This is clearly seen on Seabee Creek in 2011 and 2012, where 2011 had a much higher but shorter peak in discharge and SSC than in 2012. The gradient of a watershed also affects the runoff regime, with low gradient watersheds having a lower potential for runoff and generally experiencing greater evapotranspiration (McNamara et al. 1998).

6 Conclusions

This thesis presents an initial assessment of suspended sediment transport on rivers that were part of two projects on the North Slope of Alaska. Data collection efforts varied, with a much larger quantity collected on the rivers of the Umiat Project than in the NPR-A. The rivers considered varied quite dramatically in size and gradient between the two projects, with the rivers of the Umiat Project being considerably larger in terms of drainage area, and the NPR-A rivers being further north and on the coastal plain, thereby having lower gradient watersheds. In addition much larger values of SSC were recorded on the Umiat Rivers. As hypothesized, it appears that the majority of suspended sediment transport occurred during spring melt on all the rivers. This was confirmed on the Anaktuvuk and Chandler Rivers, where 94% and 91% of all suspended sediment discharge occurred during the last week of May in 2011; less than 40% of water discharge occurred during the same time period of 2011. In addition, spring snow conditions clearly affected SSC patterns. This is seen on Seabee Creek, where a slow melt in 2012 due to lower temperatures led to a decrease in discharge and a significant decrease in peak SSC values from 2011. It is also clear that every river reacted differently to environmental inputs such as rainfall, as well as having sediment transport regimes that were influenced by basin size and gradient. Larger watersheds will typically have summer rain storms cover a smaller percentage of area than a small basin, meaning that rainfall does not typically affect the hydrograph as strongly. In addition the gradient of the watershed also matters; this is clear when comparing hydrographs of the Anaktuvuk River and Itkillik River. The Anaktuvuk River gauge site is at a much lower elevation that that of the Itkillik, as well as having a larger watershed with a lower gradient. The Itkillik River appears to react more strongly and faster to summer rain events than the Anaktuvuk River because of the characteristics of its basin.

Clearly these two years of data collection are a foundation, but further research is necessary to gain a clearer understanding of sediment transport in rivers in arctic Alaska. Towards this effort, data collection will continue through the summer of 2013 and hopefully beyond. A main goal will be increased data collection, especially of depth-integrated samples on the Umiat Corridor rivers. The Itkillik River had a dearth of depth-integrated samples collected in the summers of 2011 and 2012, and this hindered analysis of sediment transport. In addition, increased depth-integrated samples will be collected on all rivers, including at varying locations within the cross-section. Along with this increased sampling of SSC, grain-size analysis of suspended sediments will also begin in the summer of 2013.

Also in the future it would be interesting to develop different rating curves for different parts of the flow season. The spring melt would be expected to have a different rating curve than during base flow, and summer rain storms should also produce unique rating curves. This has been done for other arctic rivers with interesting results (Forbes and Lamoureux 2005). As well as creating distinctive rating curves to account for temporal changes in SSC, hysteresis curves can provide clues about the sediment transport regime of a river (Lewkowicz and Wolfe 1994; McDonald 2007; McDonald and Lamoreux 2009). Hysteresis curves are used to evaluate both spatial and temporal variability in sediment, and are frequently used in hydrology to correlate SSC and discharge at different times of the flow season. For example, in the arctic the rising limb of the hydrograph during spring snowmelt will typically carry more sediment than the same discharge on the falling limb of the hydrograph; this would be well shown with a hysteresis curve (McDonald 2007). Future research conducted on the Anaktuvuk, Chandler and Itkillik Rivers should consider the creation of hysteresis curves.

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Appendix 1 Bed Sediment Distributions

Table A1. 1 Bed sediment distribution for the Chandler and Itkillik Rivers.

	% Finer by Weight		
Diameter [mm]	**Chandler [Coarse]**	**Chandler [Fine]**	**Itkillik**
7	0	0	0
9.5	4.5	0	0
13.5	10.0	3.9	2.0
19	18.7	11.8	8.2
27	33.1	49.9	16.8
38.4	55.1	76.2	29.9
54.5	72.2	93.0	44.2
77	90.1	97.7	56.5
109	98.5	100	72.1
154	100	100	88.6
218	100	100	96.3

Table A1. 2 Bed sediment distribution for the Anaktuvuk River.

	% Finer by Weight
Diameter [mm]	**Anaktuvuk**
15.2	0
33.0	38.8
63.5	79.3
101.6	95.5
127.0	99.3

Appendix 2 Suspended Sediment Concentrations for the Anaktuvuk River

Table A2. 1 SSC values from the Isco sampler on the Anaktuvuk River in 2011.

Date	SSC [mg/L]		Date	SSC [mg/L]
5/23/11 10:38	76.39		5/31/11 9:00	20.47
5/23/11 13:40	325.52		5/31/11 15:00	9.45
5/23/11 15:30	326.67		5/31/11 21:00	31.33
5/23/11 19:40	344.30		6/1/11 3:00	22.83
5/24/11 7:40	617.85		6/1/11 9:00	22.36
5/24/11 13:00	589.31		6/1/11 15:00	22.60
5/24/11 13:40	629.64		6/1/11 21:00	12.24
5/24/11 19:40	697.31		6/2/11 3:00	8.94
5/25/11 1:40	452.82		6/2/11 9:00	10.48
5/25/11 1:40	602.63		6/3/11 0:50	14.73
5/25/11 7:40	706.86		6/3/11 12:50	21.53
5/25/11 13:00	907.60		6/3/11 15:40	9.13
5/25/11 13:40	994.79		6/4/11 15:01	0.00
5/25/11 19:40	699.73		6/6/11 15:01	0.77
5/26/11 1:40	451.70		6/7/11 15:01	1.51
5/26/11 7:40	434.53		6/8/11 15:01	2.01
5/26/11 13:40	503.38		6/9/11 15:01	1.72
5/26/11 15:00	548.38		6/10/11 15:01	3.89
5/27/11 9:00	424.26		6/11/11 15:01	1.73
5/27/11 15:00	474.52		6/12/11 15:01	0.46
5/27/11 15:59	457.66		6/13/11 15:01	0.32
5/27/11 21:00	397.27		6/14/11 15:01	0.16
5/28/11 3:00	266.57		6/15/11 15:01	0.31
5/28/11 9:00	248.98		6/16/11 15:01	5.75
5/28/11 15:00	279.92		6/17/11 15:01	0.76
5/28/11 21:00	132.22		6/18/11 15:01	3.67
5/29/11 3:00	107.51		6/19/11 15:01	1.51
5/29/11 9:00	112.32		6/20/11 15:01	1.52
5/30/11 21:00	98.20		6/21/11 15:01	0.15
5/31/11 3:00	30.60		6/22/11 15:01	1.83

Table A2. 2 SSC values from the Isco sampler on Anaktuvuk River in 2011 continued.

Date	SSC [mg/L]		Date	SSC [mg/L]
6/23/11 15:01	0.15		7/30/11 15:01	12.74
6/24/11 15:01	0.61		7/31/11 15:01	6.80
6/25/11 15:01	0.60		8/1/11 15:01	6.29
6/26/11 15:01	2.50		8/2/11 15:01	3.80
6/27/11 15:01	0.45		8/3/11 15:01	11.21
7/12/11 15:01	3.20		8/4/11 15:01	31.41
7/13/11 15:01	0.27		8/5/11 15:01	8.12
7/14/11 15:01	0.13		8/6/11 15:01	6.17
7/15/11 15:01	10.24		8/7/11 15:01	5.39
7/16/11 15:01	23.15		8/8/11 15:01	5.20
7/17/11 15:01	12.30		8/9/11 15:01	7.74
7/18/11 15:01	35.04		8/10/11 15:01	2.53
7/19/11 15:01	1.66		8/11/11 15:01	3.64
7/20/11 15:01	0.13		8/12/11 15:01	4.04
7/21/11 15:01	0.65		8/13/11 15:01	3.91
7/22/11 15:01	2.32		8/14/11 15:01	1.21
7/23/11 15:01	1.31		8/15/11 15:01	2.50
7/24/11 15:01	35.74		8/16/11 15:01	8.18
7/25/11 15:01	1.87		8/17/11 15:01	5.51
7/26/11 15:01	3.96		8/18/11 15:01	8.88
7/27/11 15:01	0.38		8/19/11 15:01	6.10
7/28/11 15:01	3.66		8/20/11 15:01	311.26
7/29/11 15:01	3.93		9/9/11 13:36	14.60

Table A2. 3 SSC values from the depth-integrating sampler on the Anaktuvuk River in 2011.

Date	SSC [mg/L]
5/25/11 14:00	1642.72
5/27/11 14:20	782.05
5/29/11 15:30	253.34
6/2/11 9:30	47.83
7/11/11 16:40	8.81

Table A2. 4 SSC values from the Isco sampler on the Anaktuvuk River in 2012.

Date	SSC [mg/L]		Date	SSC [mg/L]
6/7/12 15:00	21.88		7/23/12 11:16	6.89
6/7/12 15:00	24.90		7/24/12 15:00	4.97
6/8/12 15:00	9.28		7/25/12 15:00	1.85
6/9/12 15:00	14.70		7/26/12 15:00	3.85
6/10/12 15:00	14.21		7/27/2012 15:00	2.39
6/11/12 15:00	74.30		7/28/12 15:00	3.20
6/12/12 15:00	88.86		7/29/12 15:00	2.87
6/13/12 15:00	30.40		7/30/12 15:00	4.85
6/14/12 15:00	4.70		8/1/12 15:00	4.83
7/2/12 15:00	17.99		8/5/12 15:00	9.29
7/3/12 15:00	25.63		8/6/12 15:00	1.40
7/4/12 15:00	0.54		8/7/12 15:00	10.67
7/5/12 15:00	8.11		8/8/12 15:00	31.88
7/6/12 15:00	2.59		8/9/12 15:00	9.83
7/7/12 15:00	14.74		8/10/12 15:00	2.64
7/8/12 15:00	59.71		8/11/12 15:00	1.60
7/9/12 15:00	6.30		8/12/12 15:00	3.85
7/10/12 15:00	5.55		8/13/12 15:00	2.24
7/11/12 15:00	6.20		8/14/12 15:00	6.23
7/12/12 15:00	1.87		8/15/12 15:00	3.42
7/16/12 15:00	0.00		8/17/12 15:00	8.58
7/18/12 15:00	21.28		8/19/12 15:00	7.09
7/20/12 15:00	14.03		8/20/12 15:00	4.01
7/21/12 15:00	12.92		8/21/12 15:00	12.61
7/22/12 15:00	9.91		8/23/12 15:00	1.76
7/23/12 11:16	4.47		8/24/12 15:00	32.00

Table A2. 5 SSC values from the depth-integrating sampler on the Anaktuvuk River in 2012.

Date	SSC [mg/L]
6/7/12 16:00	92.41
7/27/12 10:15	385.04
8/25/12 11:40	3.34

Appendix 3 Suspended Sediment Concentrations for the Chandler River

Table A3. 1 SSC values from the Isco sampler on the Chandler River in 2011.

Date	SSC [mg/L]		Date	SSC [mg/L]
5/22/11 0:00	23.42		6/3/11 3:00	67.91
5/23/11 0:00	55.96		6/3/11 9:00	99.94
5/25/11 17:40	1373.37		6/5/11 15:01	92.86
5/25/11 21:00	1418.02		6/6/11 15:01	41.64
5/26/11 9:00	1299.83		6/7/11 15:01	54.42
5/26/11 15:00	2193.18		6/8/11 15:01	40.18
5/26/11 21:00	1054.93		7/9/11 17:00	89.75
5/27/11 3:00	889.28		7/28/11 15:01	109.26
5/27/11 9:00	843.13		7/29/11 15:01	60.72
5/27/11 15:00	745.36		7/30/11 15:01	58.78
5/27/11 21:00	618.91		7/31/11 15:01	10.75
5/28/11 3:00	517.33		8/1/11 15:01	58.16
5/28/11 9:00	681.89		8/2/11 15:01	25.36
5/28/11 9:00	342.67		8/3/11 15:01	19.99
5/28/11 15:00	513.27		8/4/11 15:01	375.35
5/28/11 21:00	411.39		8/5/11 15:01	457.59
5/29/11 3:00	353.04		8/6/11 15:01	144.46
5/29/11 15:00	278.22		8/7/11 15:01	70.47
5/29/11 21:00	303.78		8/8/11 15:01	34.15
5/30/11 3:00	125.43		8/9/11 15:01	15.32
5/30/11 9:00	249.34		8/10/11 15:01	12.34
5/30/11 21:00	307.50		8/11/11 15:01	15.08
5/31/11 3:00	172.37		8/12/11 15:01	13.70
5/31/11 9:00	188.29		8/13/11 15:01	4.78
5/31/11 15:00	201.68		8/14/11 15:01	59.98
5/31/11 21:00	181.59		8/15/11 15:01	110.22
6/1/11 3:00	258.55		8/16/11 15:01	286.70
6/1/11 9:00	127.07		8/17/11 15:01	306.28
6/1/11 21:00	112.59		8/18/11 15:01	104.56
6/2/11 9:00	140.12		8/19/11 15:01	75.04
6/2/11 15:00	212.06		8/20/11 15:01	22.87
6/2/11 21:00	110.02		9/9/11 12:00	21.99

Table A3. 2 SSC values from the depth-integrating sampler on the Chandler River in 2011.

Date	SSC [mg/L]
5/28/11 14:20	586.98
5/30/11 14:20	183.43
5/31/11 11:30	108.54
6/1/11 14:15	75.79
6/3/11 10:45	34.69
7/9/11 17:00	3.61

Table A3. 3 SSC values from the Isco sampler on the Chandler River in 2012.

Date	SSC [mg/L]		Date	SSC [mg/L]
6/5/12 15:00	330.78		7/21/12 15:00	13.33
6/6/12 15:00	205.24		7/22/12 15:00	278.82
6/7/12 15:00	85.52		7/22/12 15:00	13.32
6/9/12 15:00	57.29		7/23/12 15:00	49.00
6/11/12 15:00	30.48		7/27/12 14:06	23.46
7/2/12 15:00	467.93		7/27/12 14:06	53.49
7/3/12 15:00	329.24		7/28/12 15:00	24.47
7/5/12 15:00	181.39		8/2/12 15:00	7.40
7/6/12 15:00	1048.29		8/5/12 15:00	114.35
7/7/12 15:00	1203.60		8/6/12 15:00	18.34
7/8/12 15:00	1175.09		8/7/12 15:00	128.85
7/10/12 15:00	233.94		8/8/12 15:00	202.72
7/11/12 15:00	230.08		8/9/12 15:00	311.60
7/12/12 15:00	143.89		8/10/12 15:00	30.76
7/13/12 15:00	31.05		8/11/12 15:00	80.80
7/14/12 15:00	105.73		8/13/12 15:00	26.47
7/15/12 15:00	10.41		8/14/12 15:00	8.94
7/16/12 15:00	77.02		8/16/12 15:00	1.79
7/17/12 15:00	15.29		8/18/12 15:00	4.07
7/18/12 15:00	78.26		8/22/12 15:00	11.21
7/19/12 15:00	34.67		8/24/12 15:00	35.00
7/20/12 15:00	68.06			

Table A3. 4 SSC values from the depth-integrating sampler on the Chandler River in 2012.

Date	SSC [mg/L]
6/2/12 12:45	131.12
7/27/12 12:00	75.19
8/24/12 12:50	5.75

Appendix 4 Suspended Sediment Concentrations for the Itkillik River

Table A4. 1 SSC values from the Isco sampler on the Itkillik River in 2011.

Date	SSC [mg/L]		Date	SSC [mg/L]
5/24/11 10:30	194.13		7/23/11 15:01	4.18
5/24/11 16:00	424.86		7/24/11 15:01	4.09
5/24/11 22:00	1755.84		7/25/11 15:01	9.48
5/25/11 4:00	283.22		7/26/11 15:01	8.86
5/25/11 10:00	205.61		7/27/11 15:01	6.24
5/25/11 16:00	252.43		7/28/11 15:01	21.58
5/25/11 22:00	263.73		7/29/11 15:01	7.78
5/26/11 10:00	514.73		7/30/11 15:01	11.59
5/26/11 16:00	579.38		7/31/11 15:01	23.96
5/27/11 11:45	246.10		8/1/11 15:01	32.57
5/27/11 16:00	334.02		8/2/11 15:01	93.95
5/28/11 10:00	232.53		8/5/11 15:01	494.06
5/28/11 16:00	340.10		8/6/11 15:01	443.08
5/28/11 22:00	319.78		8/7/11 15:01	149.78
5/29/11 10:00	226.49		8/8/11 15:01	36.11
5/29/11 16:00	389.90		8/9/11 15:01	22.52
5/29/11 22:00	211.21		8/10/11 15:01	12.71
7/12/11 15:01	9.24		8/11/11 15:01	17.47
7/13/11 15:01	7.49		8/12/11 15:01	11.57
7/14/11 15:01	693.08		8/13/11 15:01	10.85
7/15/11 15:01	214.22		8/14/11 15:01	5.40
7/16/11 15:01	180.82		8/15/11 15:01	12.10
7/17/11 15:01	589.24		8/16/11 15:01	8.51
7/18/11 15:01	629.29		8/17/11 15:01	28.38
7/19/11 15:01	107.13		8/19/11 15:01	261.18
7/20/11 15:01	64.64		8/20/11 15:01	95.80
7/21/11 15:01	8.29		9/9/11 16:16	3.86

Table A4. 2 SSC values from the Isco sampler on the Itkillik River in 2012.

Date	SSC [mg/L]		Date	SSC [mg/L]
6/4/12 18:43	174.93		7/30/12 15:00	77.95
6/6/12 15:00	1227.50		7/31/12 15:00	45.45
6/8/12 15:00	3947.67		8/1/12 15:00	124.09
6/10/12 15:00	814.12		8/2/12 15:00	33.97
6/12/12 15:00	917.08		8/3/12 15:00	68.61
6/14/12 15:00	64.11		8/4/12 15:00	166.61
6/16/12 15:00	31.81		8/5/12 15:00	1670.40
6/18/12 15:00	50.87		8/6/12 15:00	1101.09
6/20/12 15:00	39.90		8/7/12 15:00	2341.60
6/22/12 15:00	27.87		8/9/12 15:00	231.26
6/24/12 15:00	30.55		8/10/12 15:00	22.38
6/26/12 15:00	130.79		8/11/12 15:00	119.60
6/28/12 15:00	26.07		8/12/12 15:00	35.00
7/2/12 15:00	47.42		8/13/12 15:00	283.02
7/4/12 15:00	8.72		8/14/12 15:00	120.35
7/6/12 15:00	216.27		8/15/12 15:00	45.23
7/8/12 15:00	52.08		8/16/12 15:00	209.62
7/10/12 15:00	21.15		8/17/12 15:00	20.91
7/12/12 15:00	18.03		8/18/12 15:00	184.30
7/14/12 15:00	38.44		8/19/12 15:00	50.05
7/16/12 15:00	550.36		8/20/12 15:00	17.82
7/18/12 15:00	713.10		8/21/12 15:00	35.45
7/22/12 15:00	802.28		8/22/12 15:00	62.71
7/28/12 9:45	13.52		8/23/12 15:00	993.14
7/28/12 9:45	47.68		8/24/12 15:00	23.54
7/28/12 15:00	38.50		8/25/12 15:00	1316.81
7/29/12 15:00	212.43		8/26/12 9:39	12.20

Table A4. 3 SSC values from the depth-integrating sampler on the Itkillik River in 2012.

Date	SSC [mg/L]
7/28/12 12:40	3.73
8/26/12 13:10	1.49

Appendix 5 Suspended Sediment Concentrations for Prince Creek

Table A5. 1 SSC values from the Sigma sampler on Prince Creek in 2011.

Date	SSC [mg/L]		Date	SSC [mg/L]
6/6/11 14:20	5.85		7/11/11 11:45	170.56
6/7/11 14:20	28.71		7/12/11 11:45	55.29
6/8/11 14:20	39.70		7/13/11 11:45	23.46
6/9/11 14:20	140.24		7/14/11 11:45	47.92
6/10/11 14:20	16.18		7/15/11 11:45	33.44
6/11/11 14:20	0.61		7/16/11 11:45	12.65
6/12/11 14:20	11.54		7/17/11 11:45	13.41
6/13/11 14:20	14.78		7/18/11 11:45	308.91
6/14/11 14:20	3.61		7/19/11 11:45	134.61
6/15/11 14:20	19.37		7/20/11 11:45	71.74
6/16/11 14:20	13.88		7/21/11 11:45	54.55
6/17/11 14:20	4.62		7/22/11 11:45	24.75
6/18/11 14:20	12.09		7/23/11 11:45	28.81
6/19/11 14:20	4.85		7/24/11 11:45	19.59
6/20/11 14:20	4.67		7/25/11 11:45	19.77
6/21/11 14:20	2.70		7/26/11 11:45	3.12
6/22/11 14:20	7.34		7/27/11 11:45	4.56
6/23/11 14:20	1.36		7/28/11 11:45	9.07
6/24/11 14:20	6.21		7/29/11 11:45	4.44
6/25/11 14:20	7.40		7/30/11 11:45	2.33
6/26/11 14:20	4.14		7/31/11 11:45	13.20
6/27/11 14:20	3.00		8/1/11 11:45	43.13
6/28/11 14:20	4.32		8/2/11 11:45	12.92
6/29/11 14:20	2.70		8/29/11 0:00	0.56
7/10/11 0:00	2.35			

Table A5. 2 SSC values from the Sigma sampler on Prince Creek in 2012.

Date	SSC [mg/L]		Date	SSC [mg/L]
5/27/12 17:30	5.29		6/20/12 7:02	14.24
5/26/12 7:00	96.79		6/21/12 7:02	19.19
5/26/12 19:00	18.38		6/22/12 7:02	24.15
5/27/12 7:00	10.94		6/23/12 7:02	13.83
5/27/12 19:00	30.78		6/25/12 7:02	3.93
5/28/12 7:00	25.19		6/25/12 7:02	11.30
5/28/12 19:00	13.37		6/26/12 7:02	12.52
5/29/12 7:00	89.79		6/27/12 7:02	9.03
1/0/00 12:00	351.92		6/28/12 7:02	17.62
1/1/00 0:00	759.64		6/29/12 7:02	13.18
1/1/00 12:00	777.35		6/30/12 7:02	6.50
1/2/00 0:00	259.18		7/1/12 7:02	9.04
1/2/00 12:00	142.55		7/2/12 7:02	7.70
1/3/00 0:00	199.80		7/5/12 19:20	1.30
1/3/00 12:00	190.16		7/8/12 7:02	28.83
1/4/00 0:00	134.98		7/9/12 7:02	25.23
1/4/00 12:00	240.00		7/10/12 7:02	11.00
1/5/00 0:00	97.34		7/11/12 7:02	4.64
1/5/00 12:00	141.89		7/12/12 7:02	12.17
6/5/12 19:30	117.07		7/13/12 7:02	17.87
6/10/12 7:02	10.03		7/14/12 7:02	19.69
6/11/12 7:02	14.90		7/15/12 7:02	11.71
6/12/12 7:02	5.64		7/16/12 7:02	1.07
6/13/12 7:02	9.86		7/17/12 7:02	2.68
6/15/12 7:02	2.66		7/18/12 7:02	2.49
6/15/12 7:02	24.00		7/19/12 7:02	4.08
6/16/12 7:02	12.41		7/20/12 7:02	3.03
6/18/12 7:02	15.86		9/2/12 16:15	27.77
6/19/12 7:02	12.90			

Appendix 6 Suspended Sediment Concentrations for Seabee Creek

Table A6. 1 SSC values from the Isco sampler on Seabee Creek in 2011.

Date	SSC [mg/L]		Date	SSC [mg/L]
5/28/11 3:30	3.67		6/16/11 15:30	3.07
5/28/11 15:30	4.47		6/17/11 15:30	0.14
5/29/11 15:30	11.20		6/18/11 15:30	0.58
5/30/11 3:30	52.45		6/19/11 15:30	3.44
5/30/11 15:30	29.76		6/20/11 15:30	3.45
5/31/11 3:30	15.43		6/21/11 15:30	3.83
5/31/11 15:30	19.44		6/22/11 15:30	3.14
6/1/11 3:30	3.68		6/23/11 15:30	5.70
6/1/11 15:30	5.88		6/24/11 15:30	2.26
6/2/11 3:30	5.14		6/25/11 15:30	3.37
6/2/11 15:30	0.59		6/26/11 15:30	1.73
6/3/11 3:30	7.22		6/27/11 15:30	2.97
6/3/11 15:30	0.30		6/28/11 15:30	2.95
6/4/11 3:30	0.77		6/29/11 15:30	2.05
6/4/11 15:30	3.16		6/30/11 15:30	1.88
6/5/11 3:30	4.46		7/1/11 15:30	0.00
6/5/11 15:30	24.60		7/7/11 3:30	13.85
6/6/11 3:30	1.66		7/8/11 3:30	21.90
6/6/11 15:30	1.30		7/9/11 3:30	2.90
6/7/11 3:30	109.96		7/10/11 3:30	7.76
6/7/11 15:30	22.53		7/11/11 3:30	5.06
6/8/11 3:30	33.58		7/12/11 3:30	10.61
6/8/11 15:30	10.09		7/13/11 3:30	139.91
6/9/11 15:30	134.56		7/14/11 3:30	16.55
6/10/11 15:30	29.49		7/15/11 3:30	20.87
6/11/11 15:30	22.97		7/16/11 3:30	29.63
6/12/11 15:30	10.67		7/17/11 3:30	29.89
6/13/11 15:30	12.24		7/18/11 3:30	12.12
6/14/11 15:30	4.89		7/19/11 3:30	18.21
6/15/11 15:30	8.49		7/20/11 3:30	66.95

Table A6. 2 SSC values from the Isco sampler on Seabee Creek in 2011 continued.

Date	SSC [mg/L]		Date	SSC [mg/L]
7/21/11 3:30	18.10		7/26/11 3:30	9.88
7/22/11 3:30	17.79		7/27/11 3:30	13.62
7/23/11 3:30	16.86		7/28/11 3:30	14.30
7/24/11 3:30	15.97		7/29/11 3:30	19.22
7/25/11 3:30	10.71		7/30/11 3:30	13.25

Table A6. 3 SSC values from the Isco sampler on Seabee Creek in 2012.

Date	SSC [mg/L]		Date	SSC [mg/L]
5/23/12 21:00	0.60		6/7/12 19:00	2.85
5/24/12 7:01	1.80		6/8/12 7:00	7.75
5/24/12 11:15	0.34		6/8/12 19:00	3.24
5/24/12 19:01	0.20		6/9/12 7:00	1.83
5/25/12 7:01	0.00		6/9/12 19:00	3.09
5/25/12 19:01	0.00		6/10/12 7:00	4.49
5/25/12 21:50	6.53		6/10/12 19:00	3.41
5/26/2012 7:01	1.30		6/11/12 7:00	5.63
5/26/12 19:01	0.60		6/11/12 18:40	2.98
5/27/12 19:01	0.30		6/11/12 19:00	8.42
41057.79236	1.01		6/12/12 7:00	5.64
5/29/12 19:01	1.10		6/13/12 14:30	5.83
5/30/12 7:01	1.94		6/14/12 14:30	13.64
5/30/12 19:01	0.89		6/15/12 14:30	2.57
5/31/12 7:01	1.19		6/16/12 14:30	1.17
5/31/12 19:01	2.75		6/17/12 14:30	2.74
6/1/12 7:01	3.35		6/18/12 14:30	0.52
6/1/12 11:45	4.01		6/19/12 14:30	1.02
6/1/12 19:01	6.31		6/20/12 14:30	0.53
6/2/12 7:01	1.68		6/21/12 14:30	2.16
6/2/12 12:43	1.48		6/22/12 14:30	0.42
6/2/2012	1.80		6/23/12 14:30	1.41
6/3/12 7:01	4.57		6/24/12 14:30	16.11
6/3/12 15:01	3.89		6/25/12 14:30	2.27
6/6/12 7:00	2.56		7/7/12 7:30	6.21
6/6/12 19:00	7.96		7/8/12 7:30	17.04
6/7/12 7:00	12.17		7/9/12 7:30	6.37

Table A6. 4 SSC values from the Isco sampler on Seabee Creek in 2012 continued.

Date	SSC [mg/L]		Date	SSC [mg/L]
7/10/12 7:30	0.33		7/18/12 7:30	9.00
7/11/12 7:30	5.25		7/19/12 7:30	6.10
7/12/12 7:30	17.69		7/20/12 7:30	7.46
7/13/12 7:30	3.32		7/21/12 7:30	5.22
7/14/12 7:30	3.68		7/22/12 7:30	6.30
7/15/12 7:30	7.03		7/23/12 7:30	10.45
7/16/12 7:30	1.95		7/24/12 7:30	7.51
7/17/12 7:30	5.36		8/31/11 14:10	38.00

Appendix 7 Suspended Sediment Concentrations for Fish Creek

Table A7. 1 SSC values from the Isco Sampler on Fish Creek in 2012.

Date	SSC [mg/L]		Date	SSC [mg/L]
5/27/12 0:00	4.90		6/28/12 14:30	176.42
6/3/12 21:16	14.36		6/29/12 14:30	156.37
6/5/12 14:00	137.00		6/30/12 14:30	121.12
6/5/12 19:00	162.66		7/1/12 14:30	107.46
6/6/12 7:00	184.29		7/2/12 14:30	119.20
6/6/12 19:00	112.17		7/3/12 14:30	50.15
6/7/12 7:00	109.57		7/7/12 16:10	1314.16
6/7/12 14:00	116.38		7/7/12 17:30	61.98
6/7/12 19:00	109.44		7/8/12 17:30	58.18
6/8/12 7:00	153.74		7/9/12 17:30	100.54
6/8/12 19:00	160.06		7/10/12 17:30	75.19
6/9/12 7:00	169.38		7/11/12 17:30	67.88
6/9/12 13:00	108.18		7/12/12 17:30	59.96
6/10/12 14:30	133.24		7/13/12 17:30	57.96
6/11/12 14:30	216.34		7/14/12 17:30	50.37
6/12/12 14:30	169.04		7/15/12 17:30	59.17
6/13/12 14:30	148.59		7/16/12 17:30	65.37
6/14/12 14:30	147.54		7/17/12 17:30	55.71
6/15/12 14:30	159.74		7/18/12 17:30	50.79
6/16/12 14:30	159.31		7/19/12 17:30	44.38
6/17/12 14:30	118.95		7/20/12 17:30	56.76
6/18/12 14:30	181.24		7/21/12 17:30	49.80
6/19/12 14:30	249.66		7/22/12 17:30	36.95
6/20/12 14:30	267.43		7/23/12 17:30	36.96
6/21/12 14:30	262.62		7/24/12 17:30	68.84
6/22/12 14:30	244.63		7/25/12 17:30	148.65
6/23/12 14:30	250.42		7/26/12 17:30	44.46
6/24/12 14:30	178.27		7/27/12 17:30	30.86
6/25/12 14:30	94.25		7/28/12 17:30	54.97
6/26/12 14:30	97.67		7/29/12 17:30	28.25
6/27/12 14:30	148.34		7/30/12 17:30	30.89